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(54) **VARIABLE CAPACITANCE WITH DELAY LOCK LOOP**

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(51) **Int. Cl.**

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**H03L 7/08** (2006.01)  
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**H03L 7/099** (2006.01)

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*H03B 2201/0266* (2013.01); *H03B 2200/005* (2013.01); *H03L 7/22* (2013.01); *H03K 7/08* (2013.01); *H03J 2200/10* (2013.01); *H03L 1/022* (2013.01); *H03L 1/026* (2013.01); *H03L 7/07* (2013.01); *H03L 7/08* (2013.01); *H03L 7/0812* (2013.01); *H03L 7/099* (2013.01); *H03B 5/1228* (2013.01); *H03B 5/1215* (2013.01); *H03B 5/1265* (2013.01)

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See application file for complete search history.

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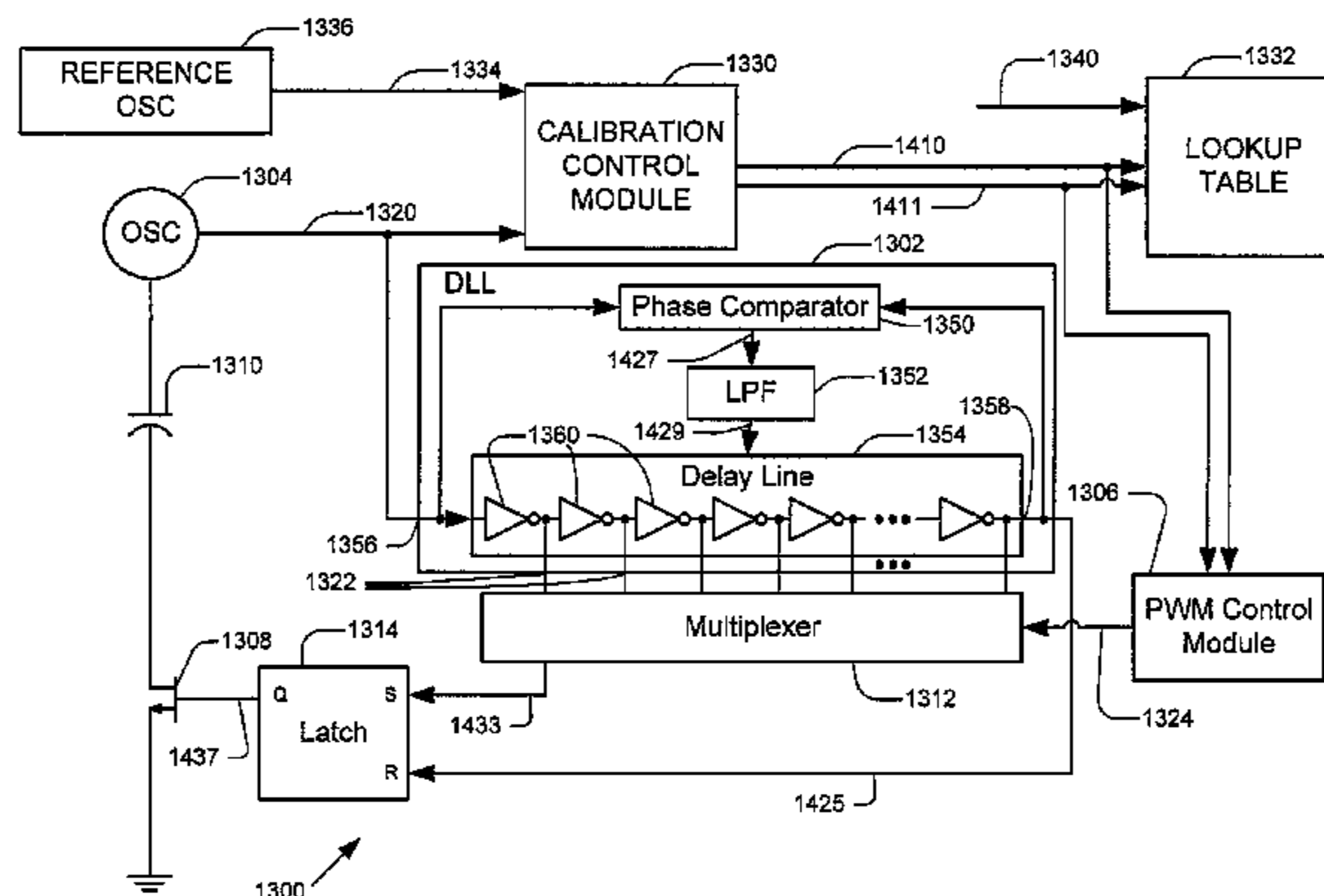
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Primary Examiner — Ryan Johnson

(57) **ABSTRACT**

An integrated circuit includes a delay lock loop (DLL) circuit that generates incremental delay line signals and a delay line output signal based on a received clock signal. A pulse-width modulation (PWM) control module generates a PWM control signal. A variable capacitance circuit is controlled based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

**21 Claims, 19 Drawing Sheets**



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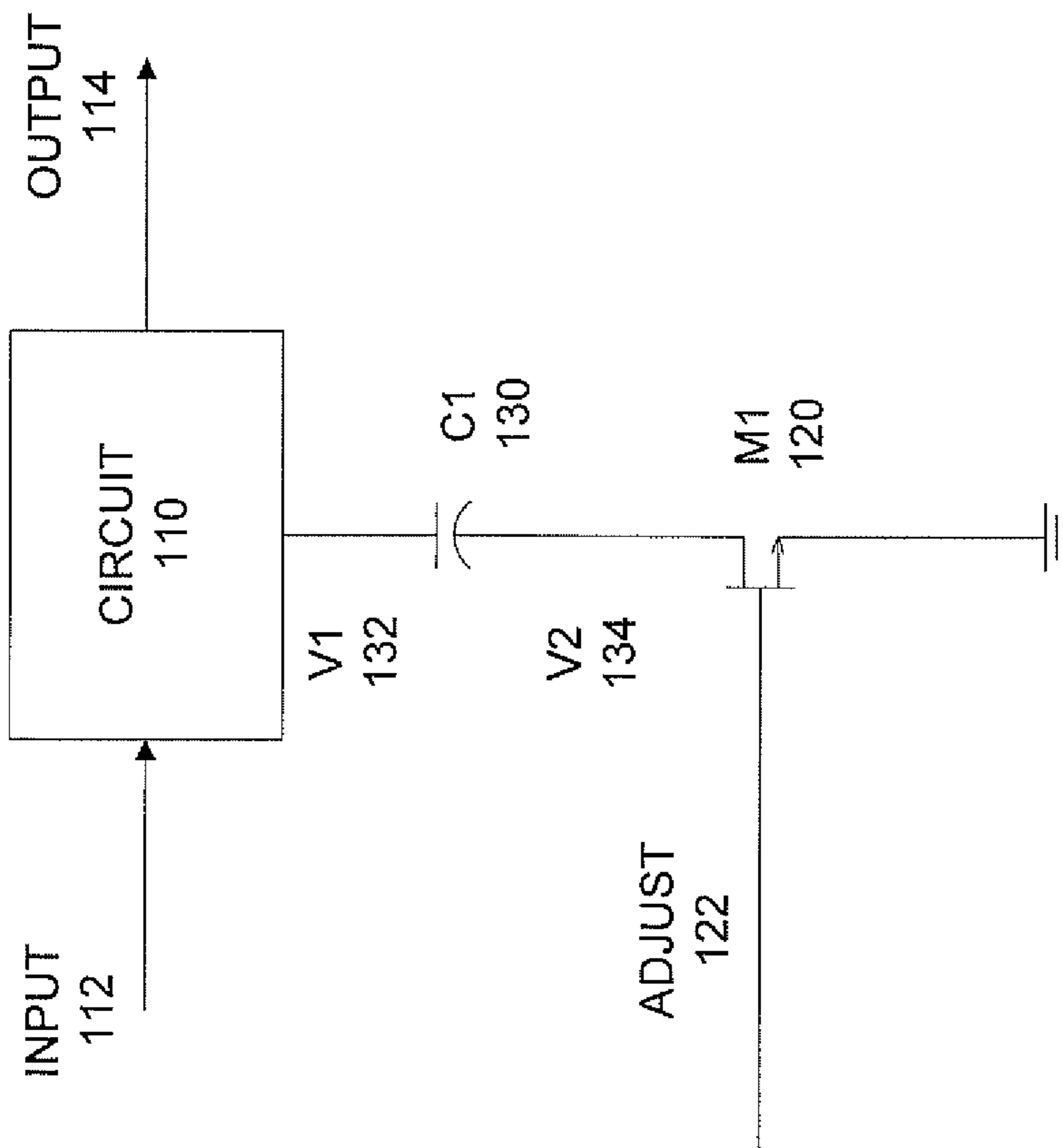
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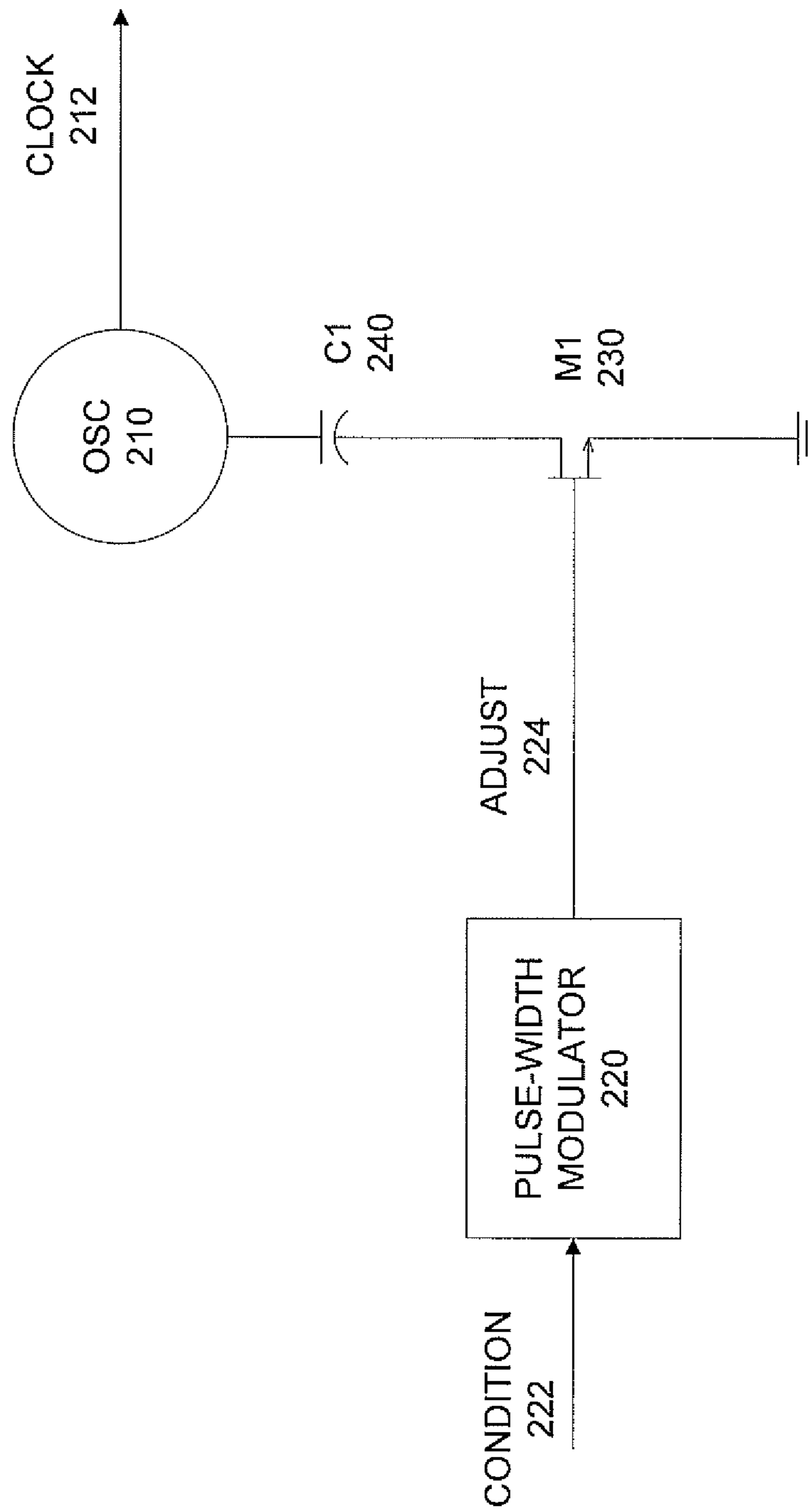
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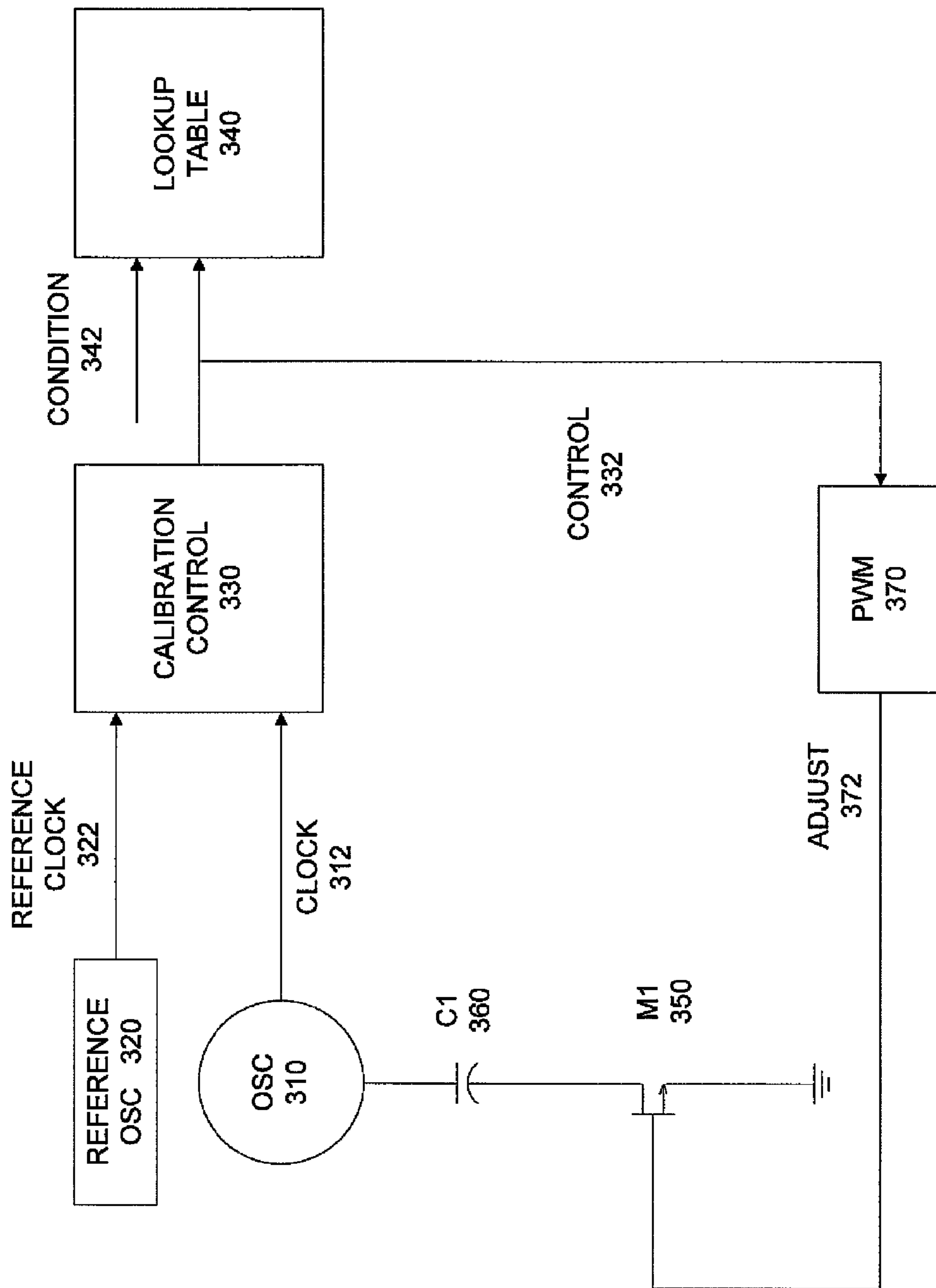
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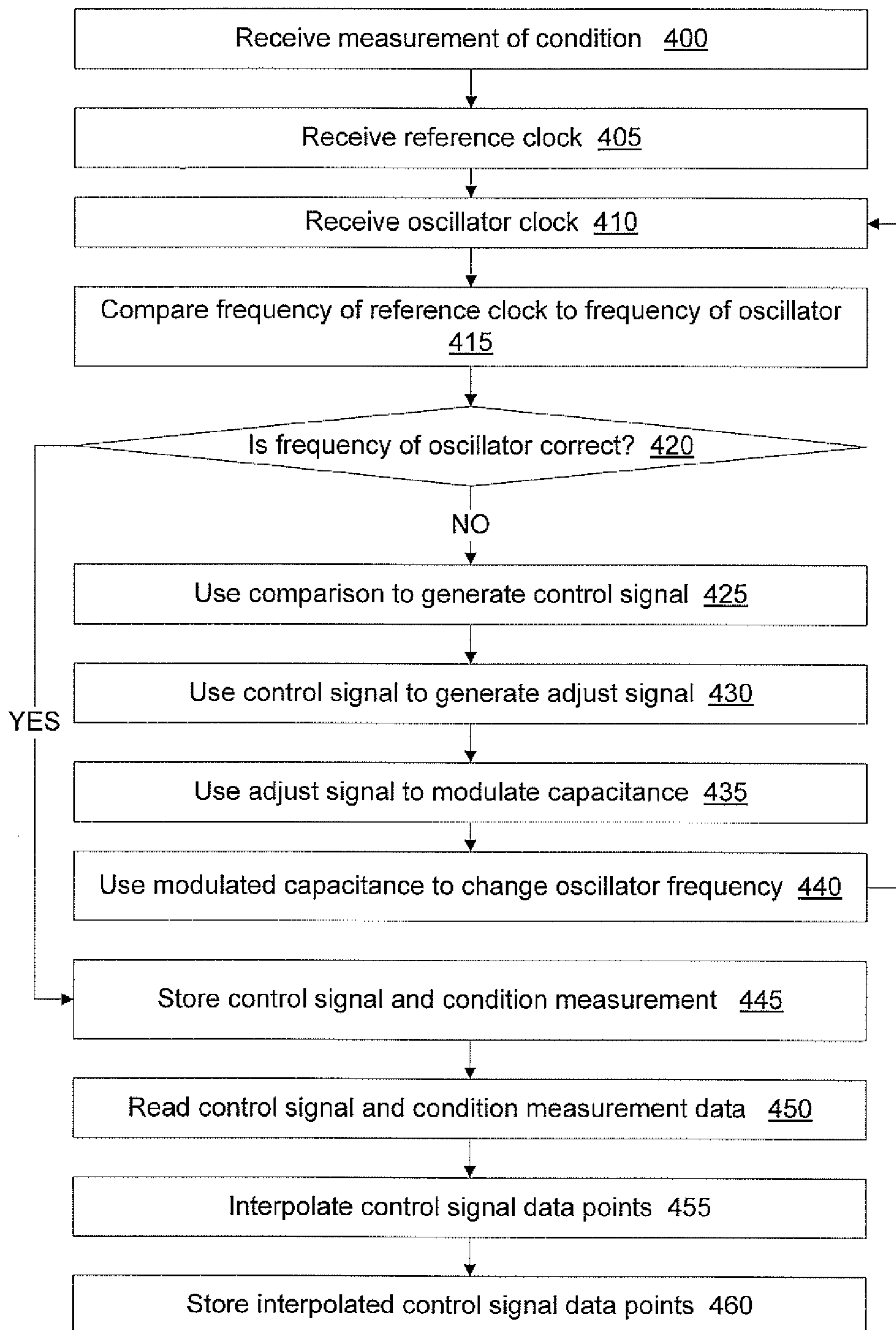
**FIG. 1**



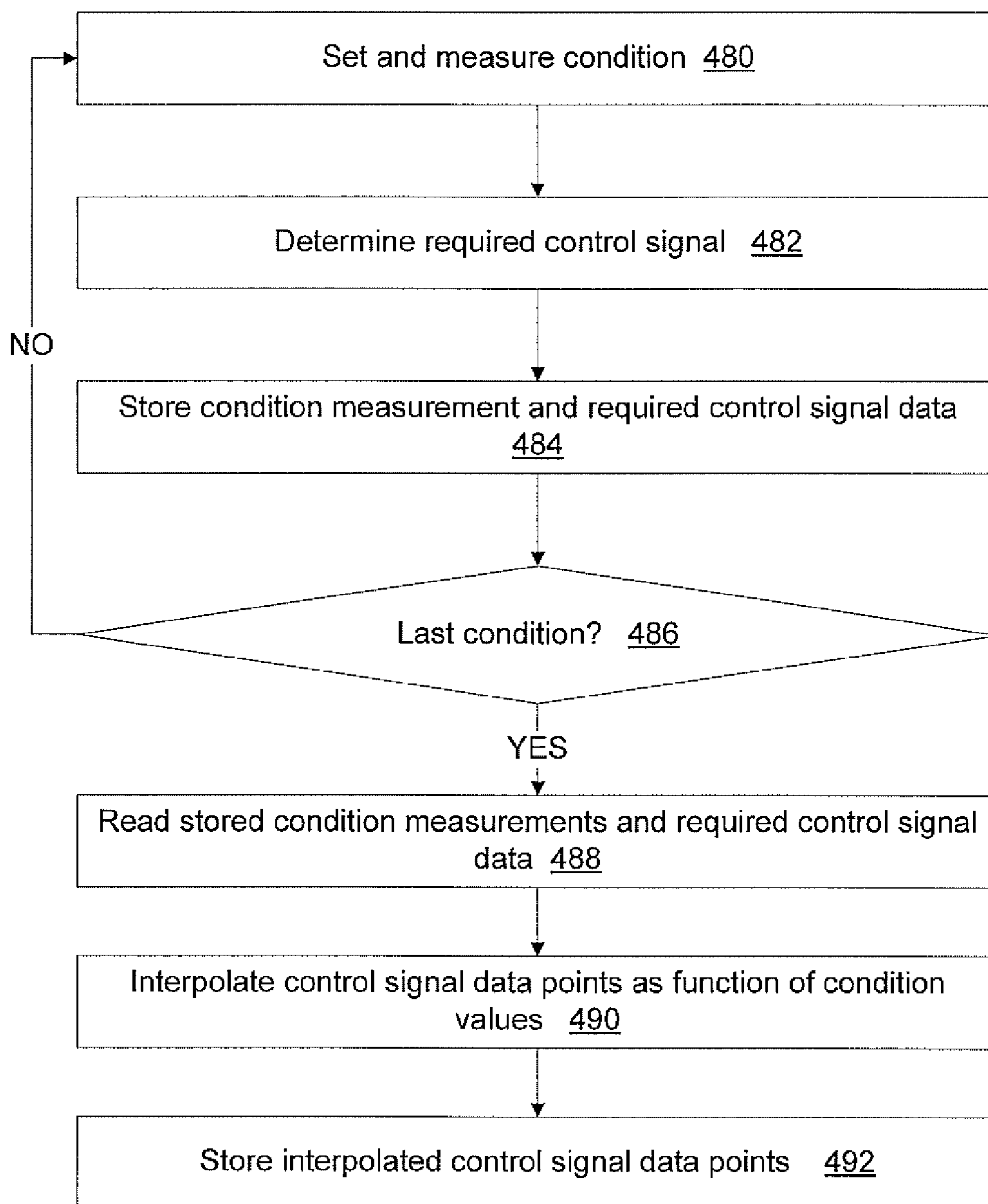
**FIG. 2**



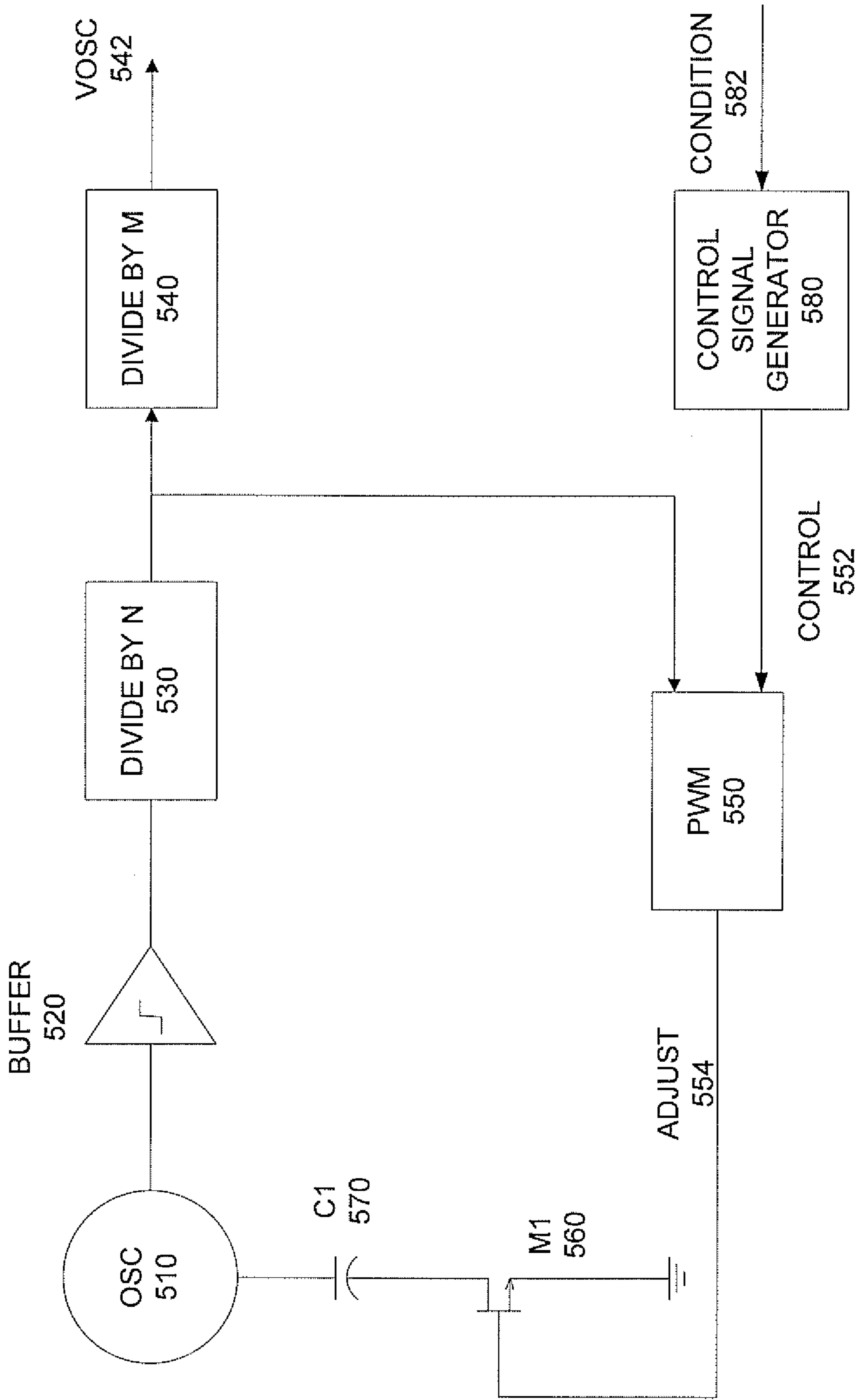
**FIG. 3**



**FIG. 4A**

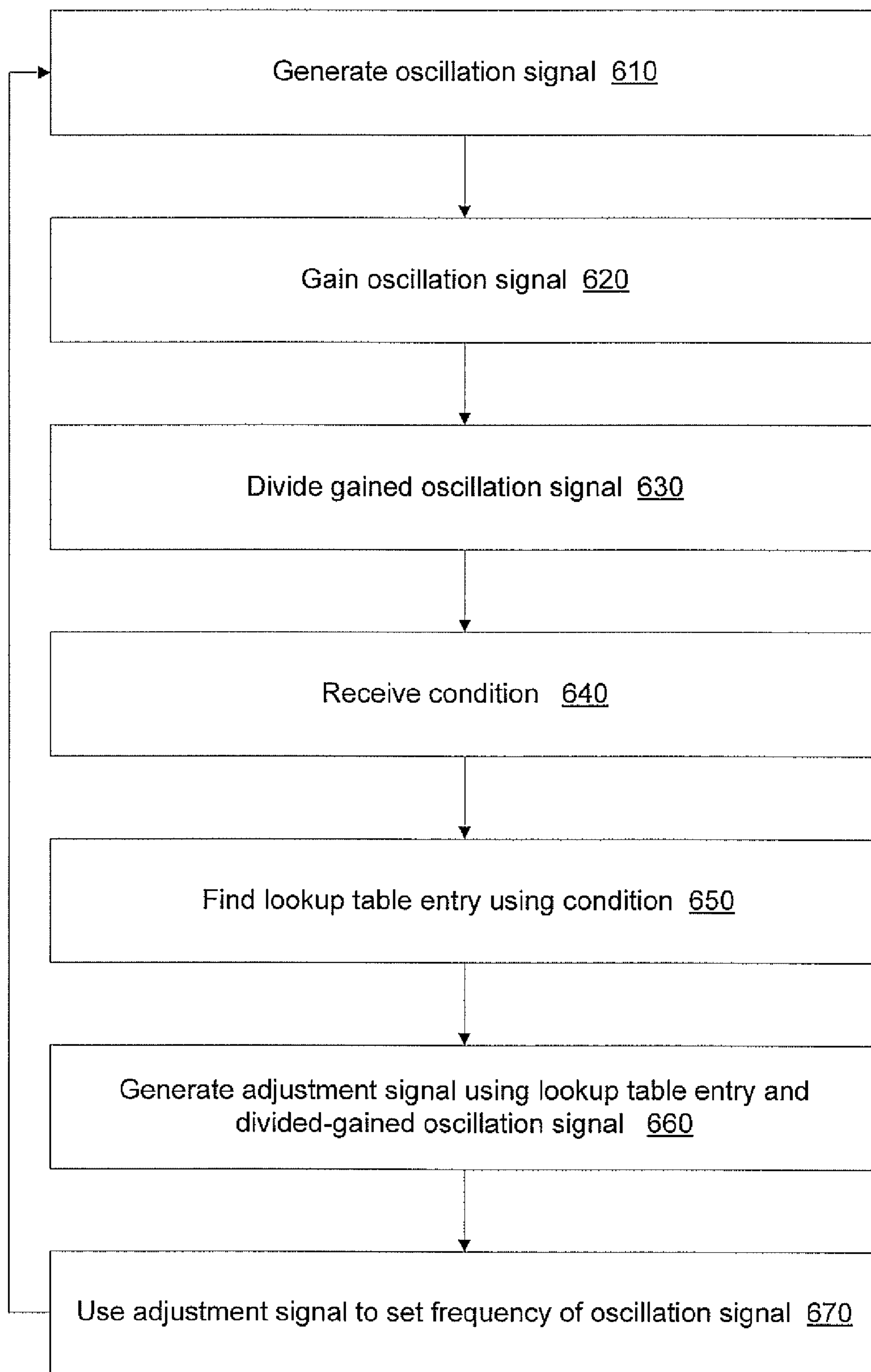


**FIG. 4B**

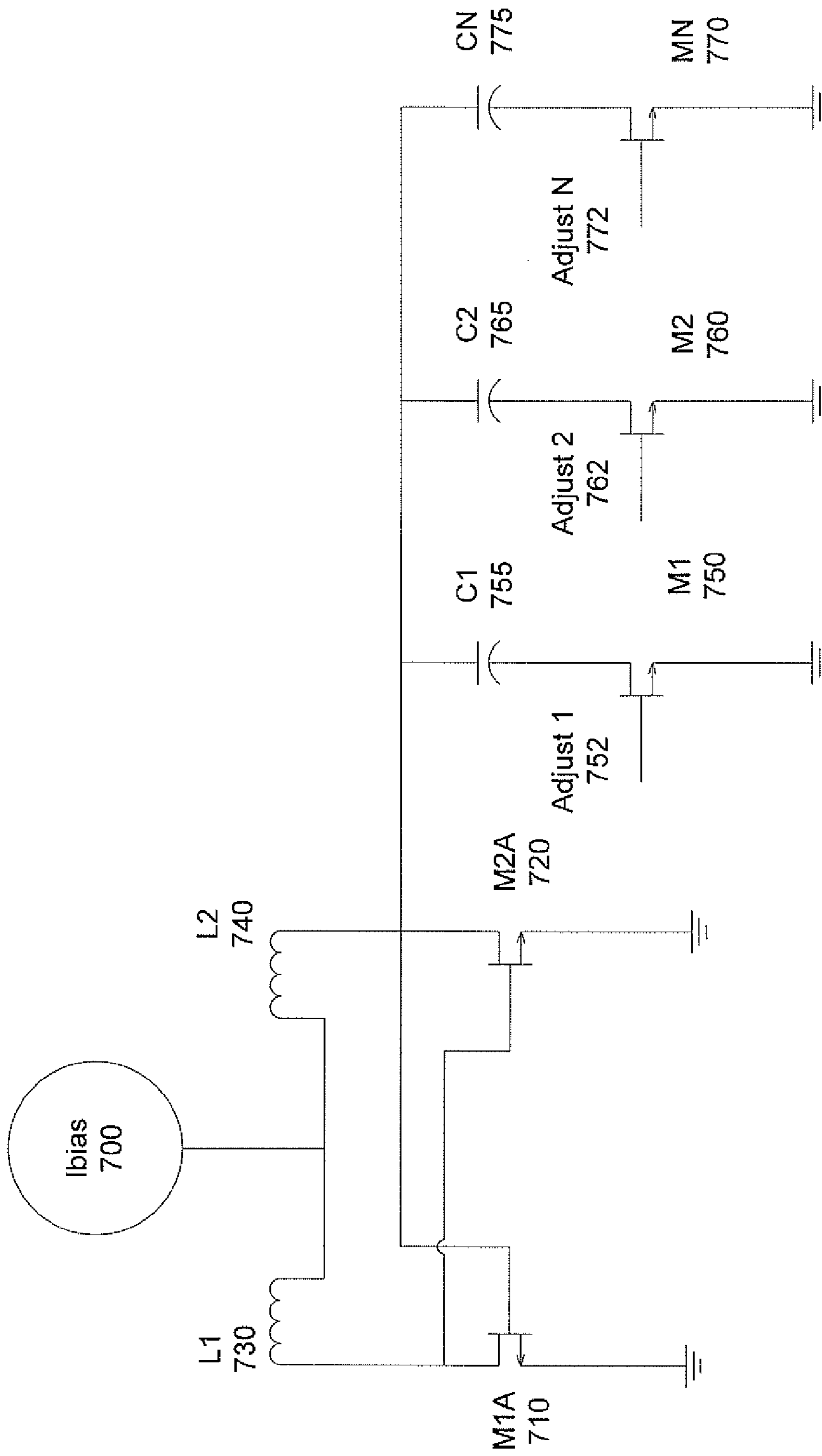


**FIG. 5**

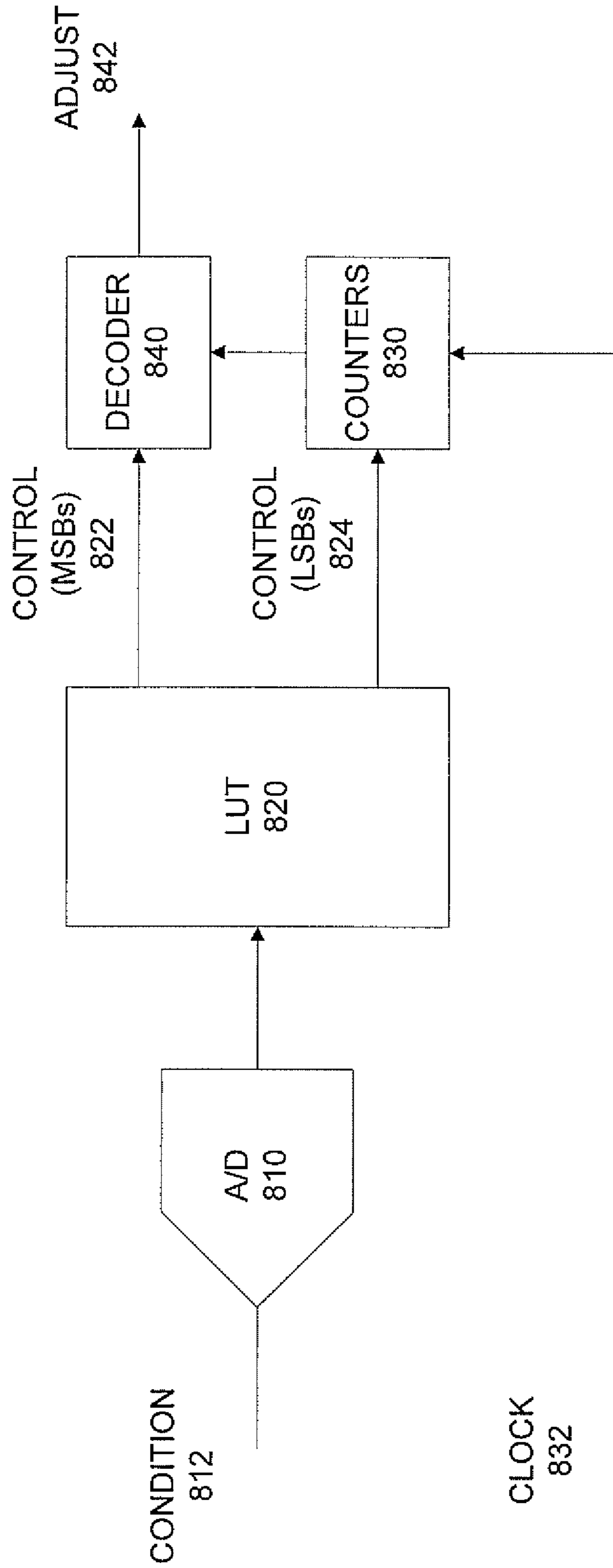




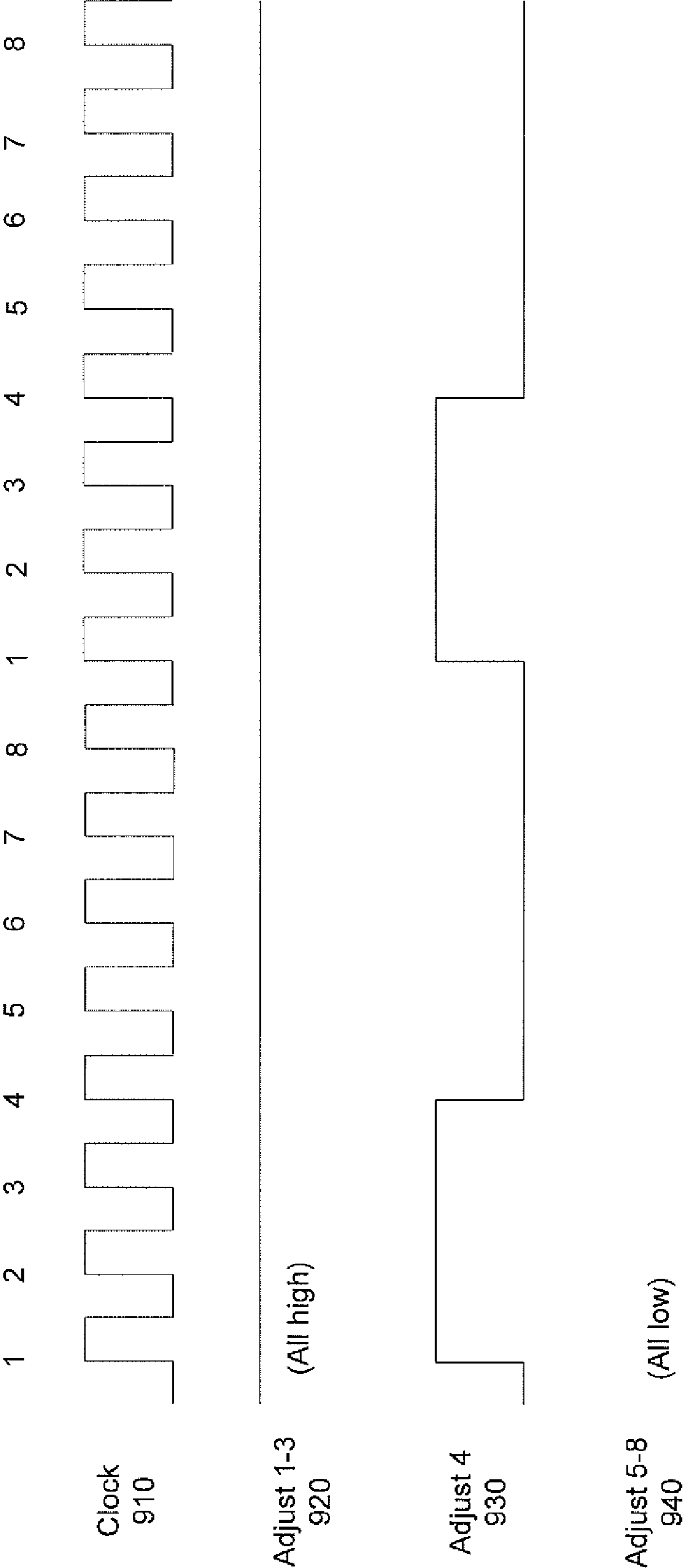
**FIG. 6**



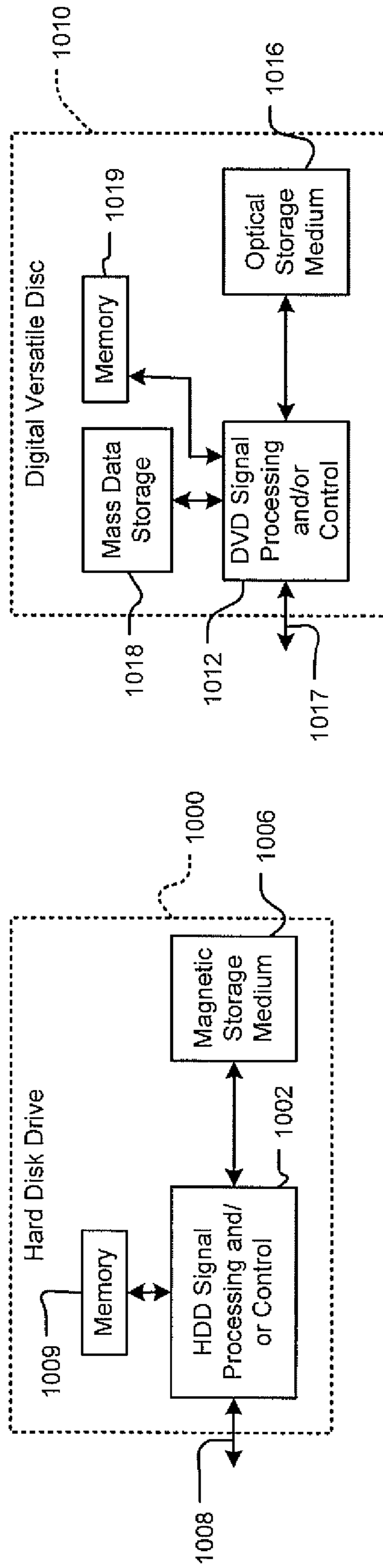
**FIG. 7**



**FIG. 8**

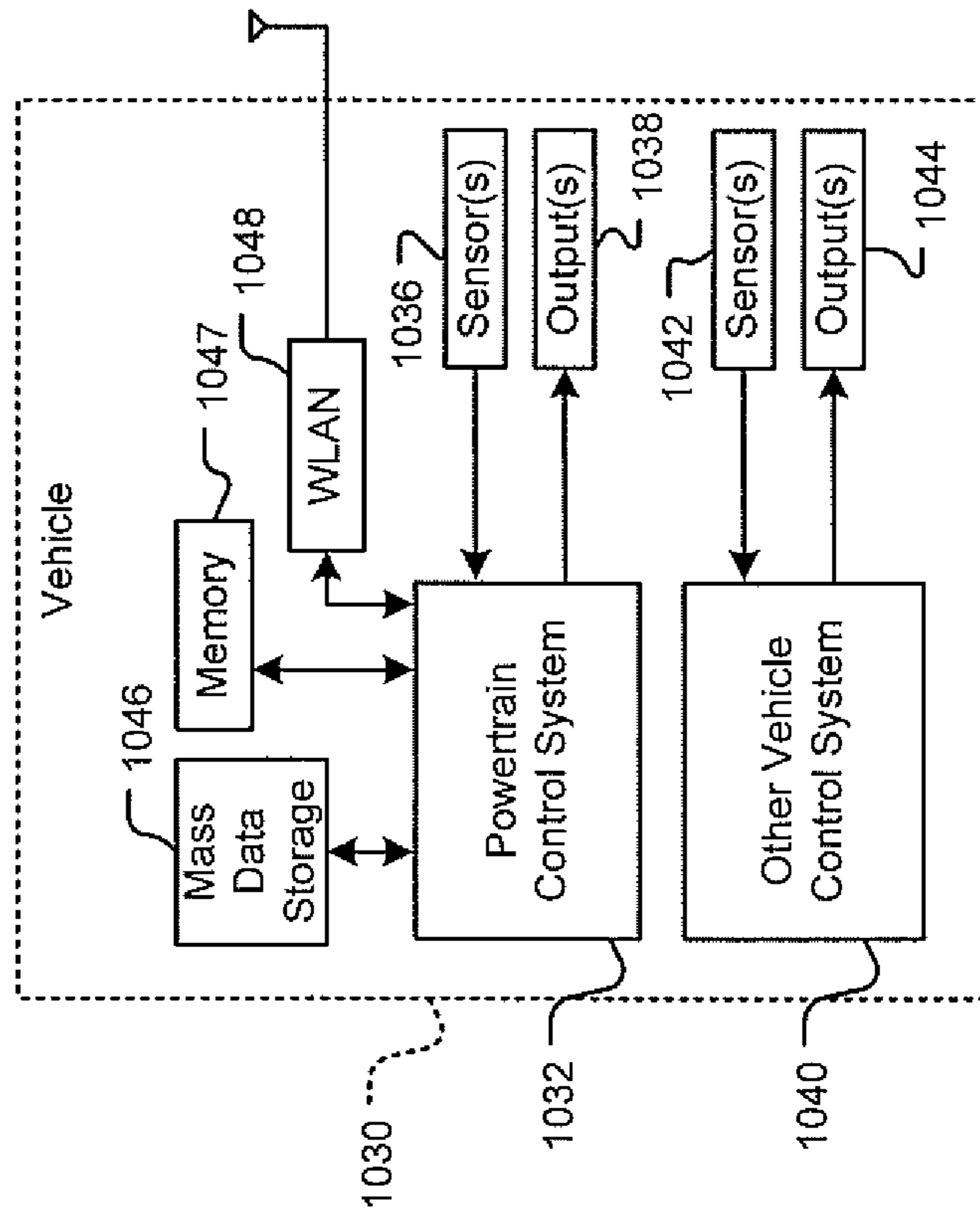


**FIG. 9**

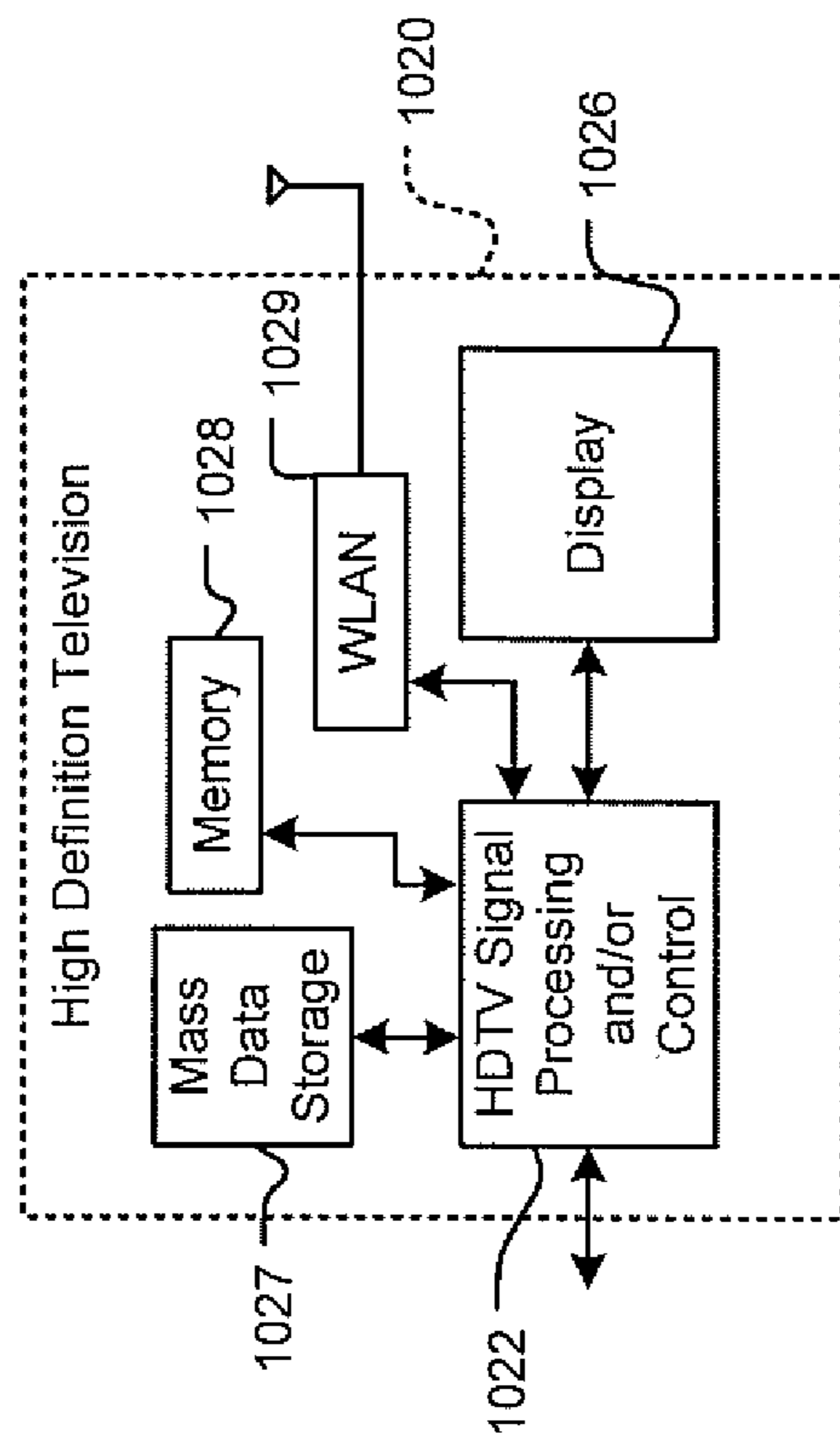


**FIG. 10A**

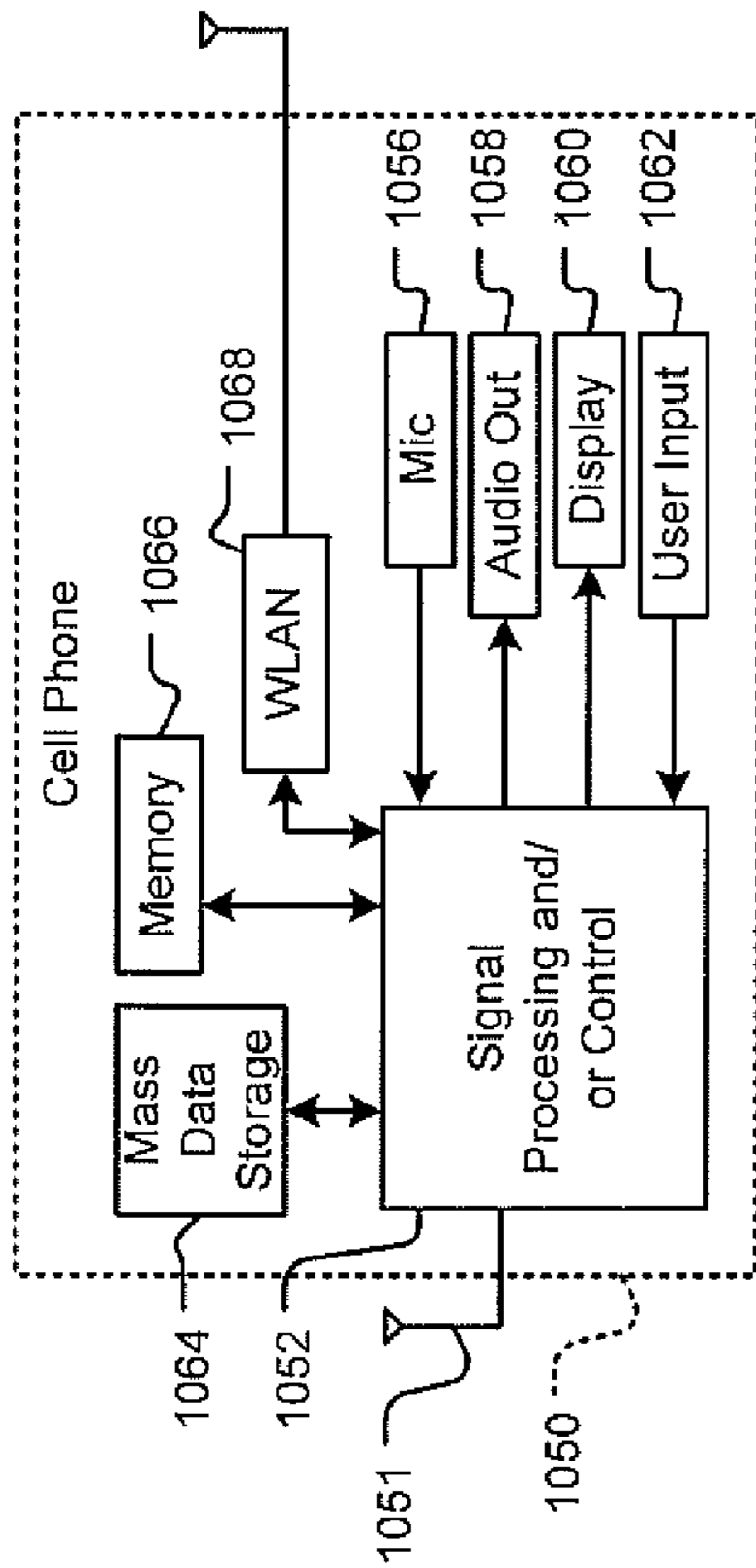
**FIG. 10B**



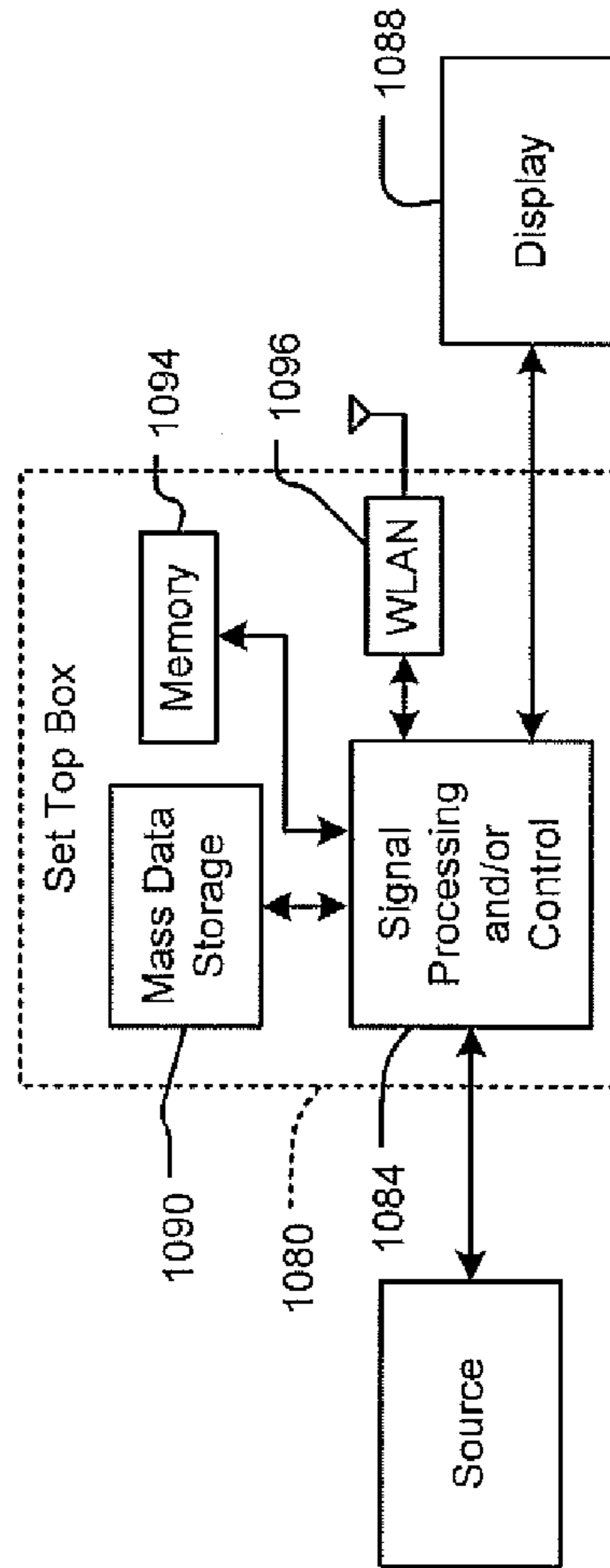
**FIG. 10D**



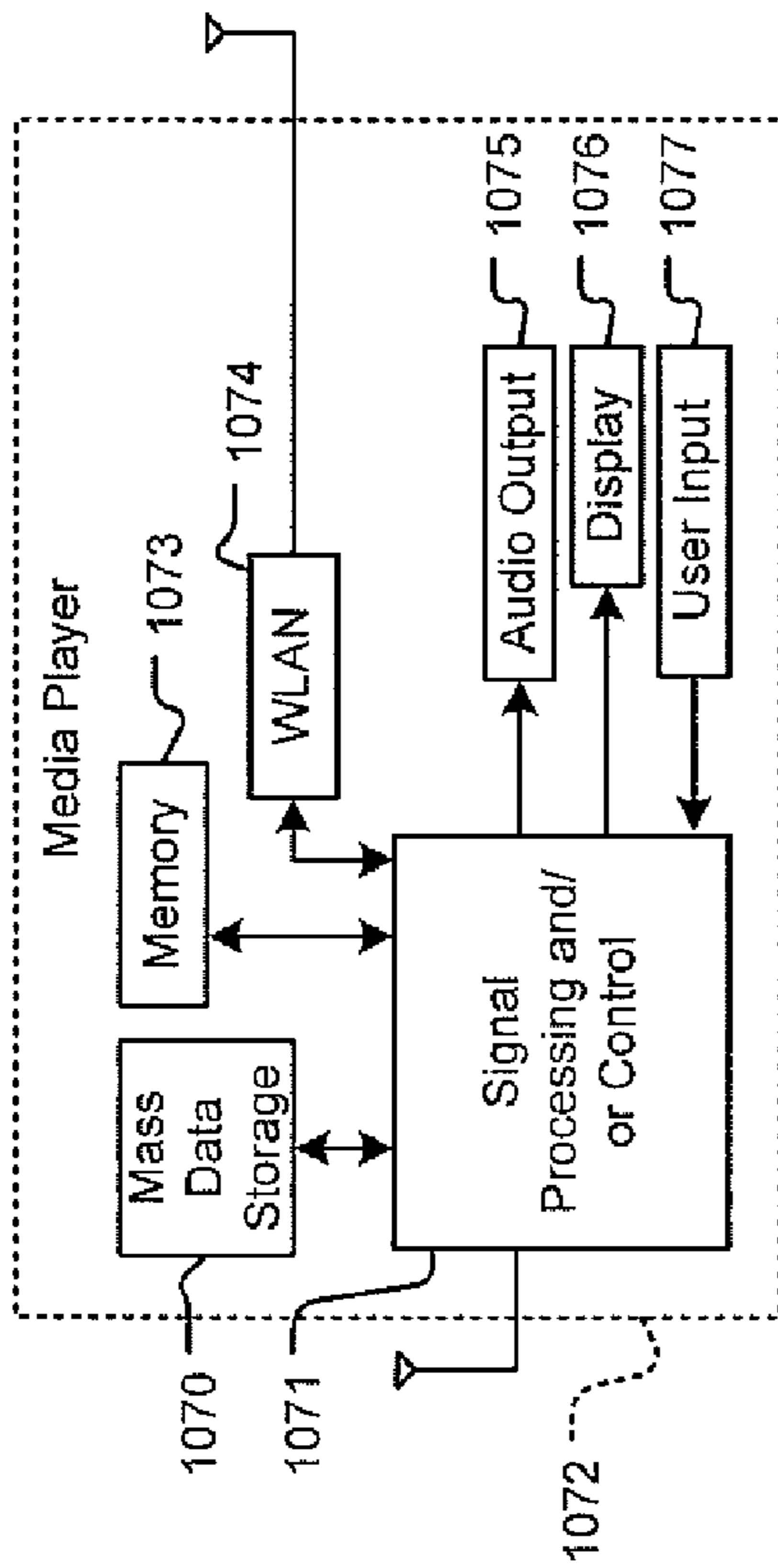
**FIG. 10C**



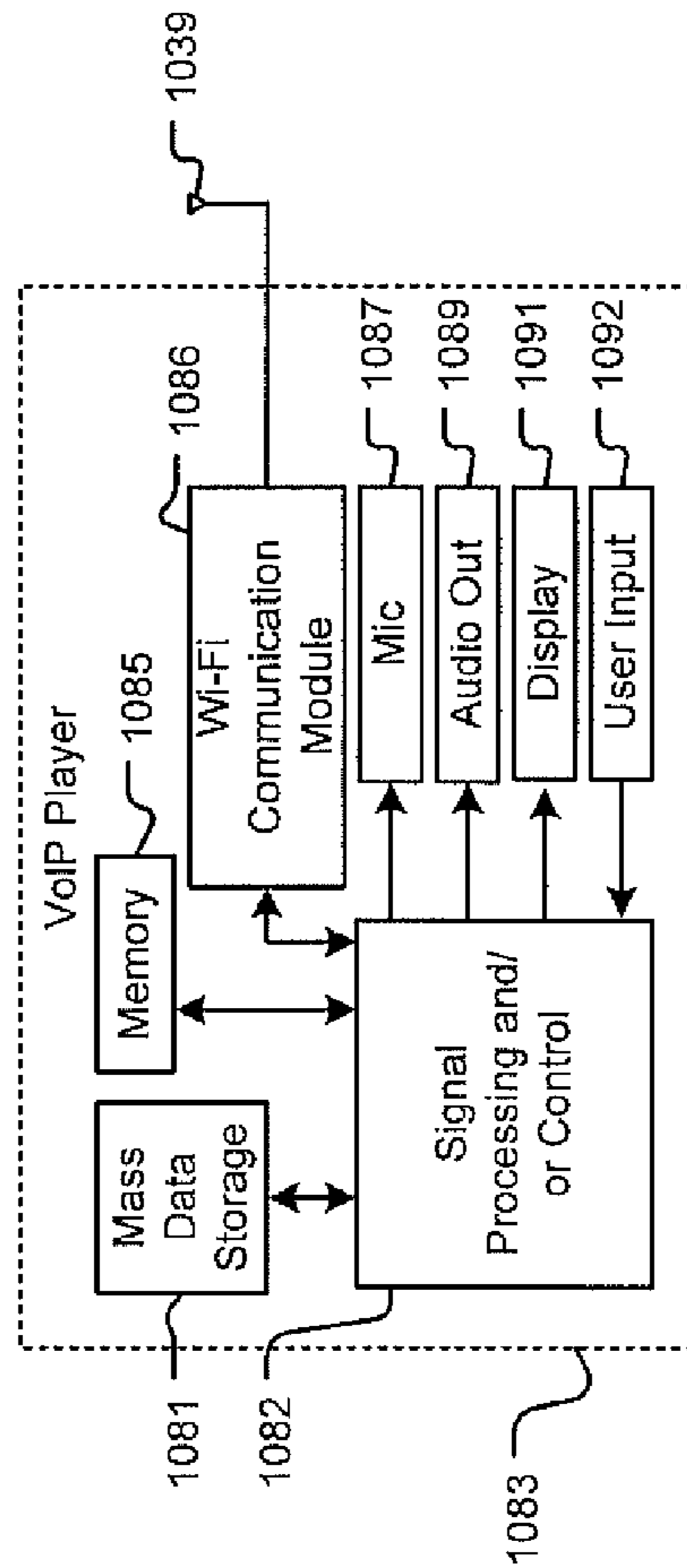
**FIG. 10E**



**FIG. 10F**

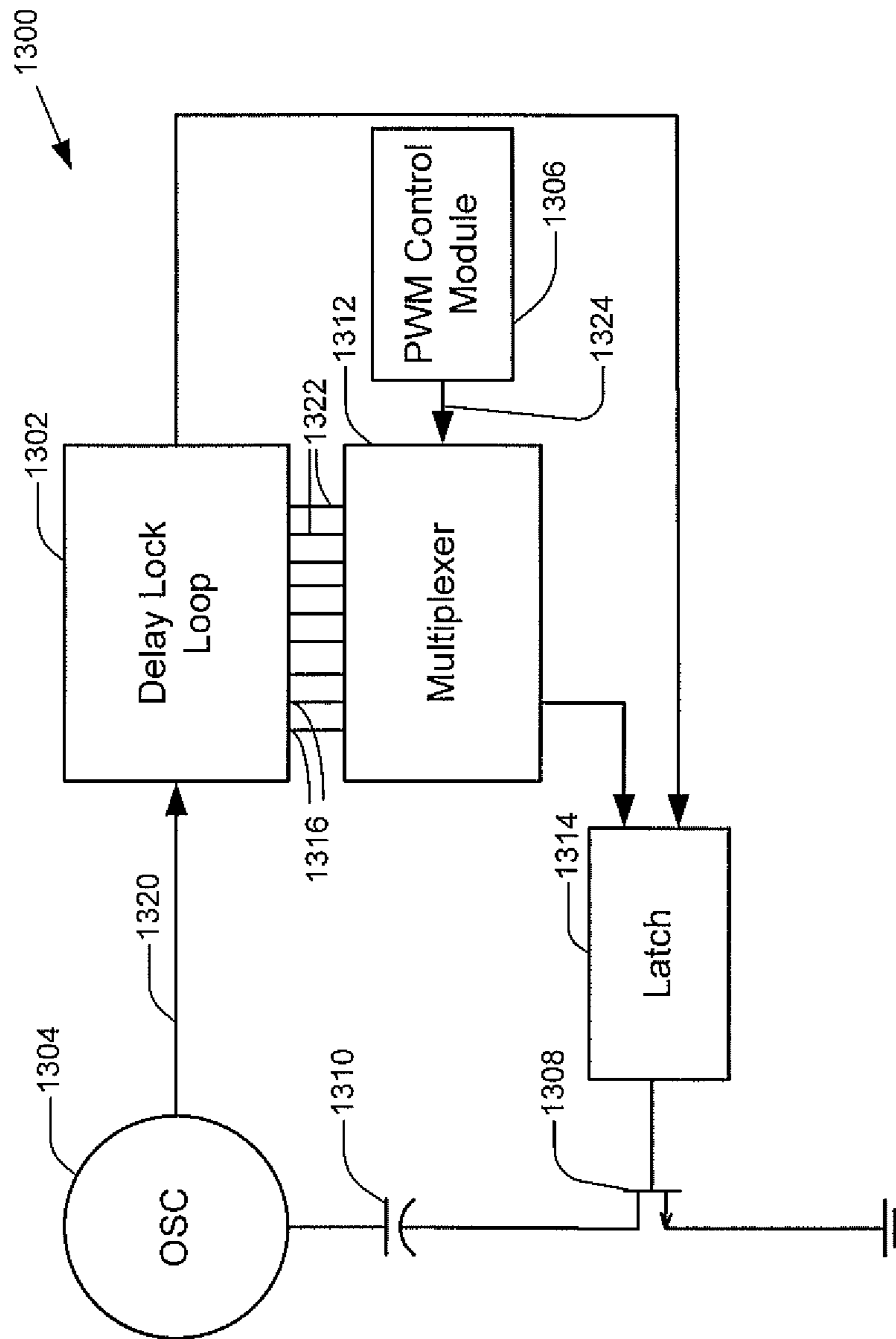


**FIG. 10G**



**FIG. 10H**





**FIG. 11**

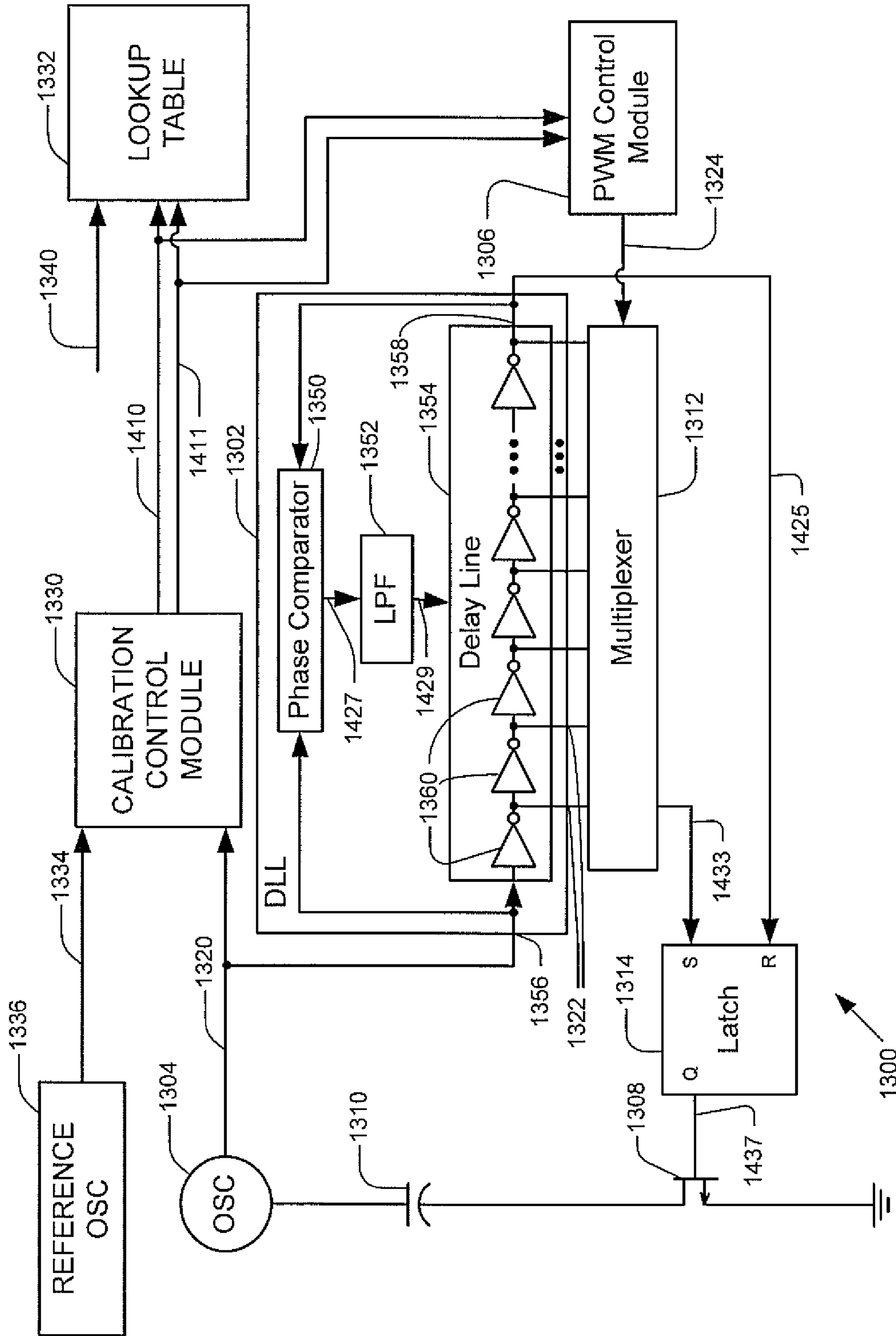
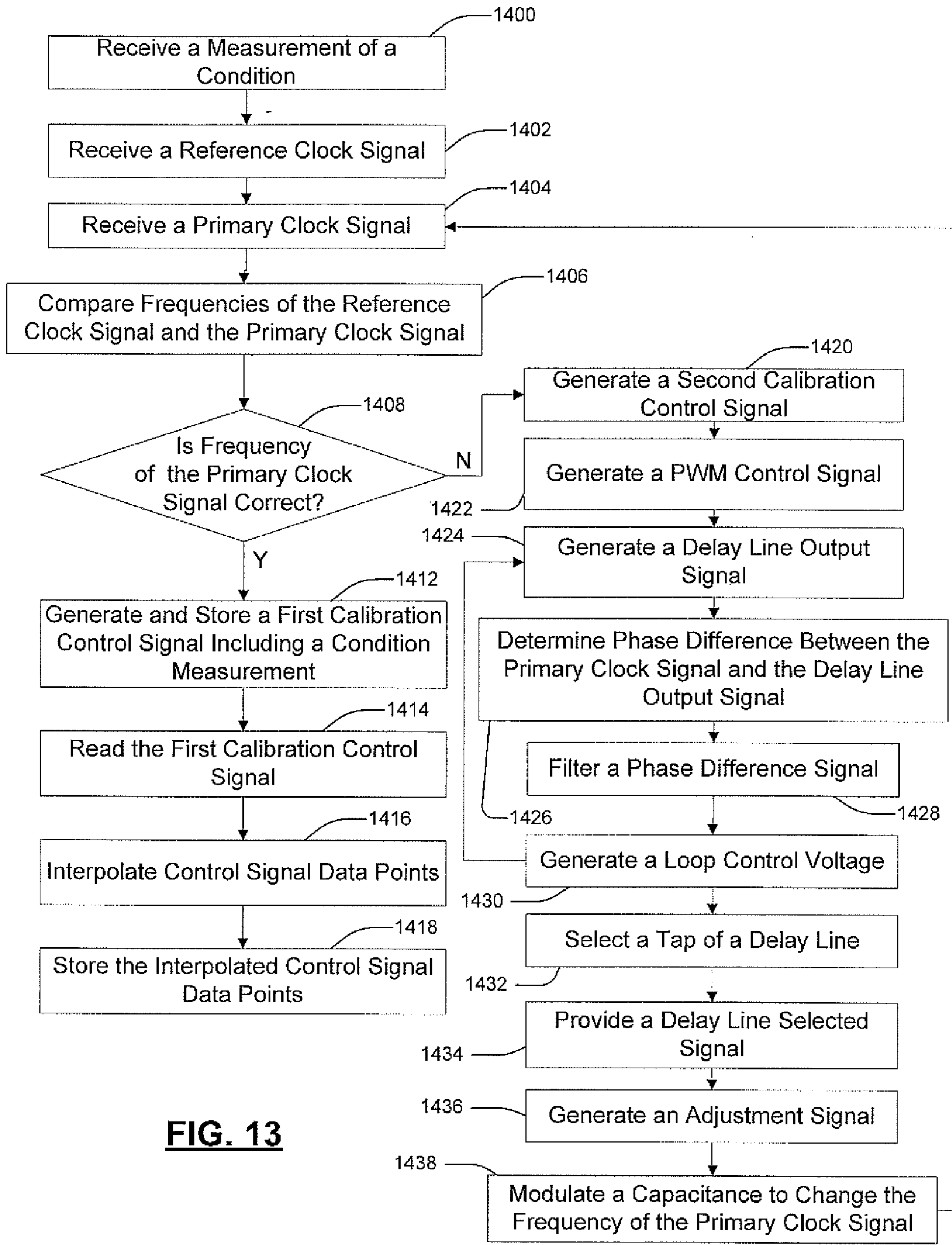


FIG. 12



**FIG. 13**

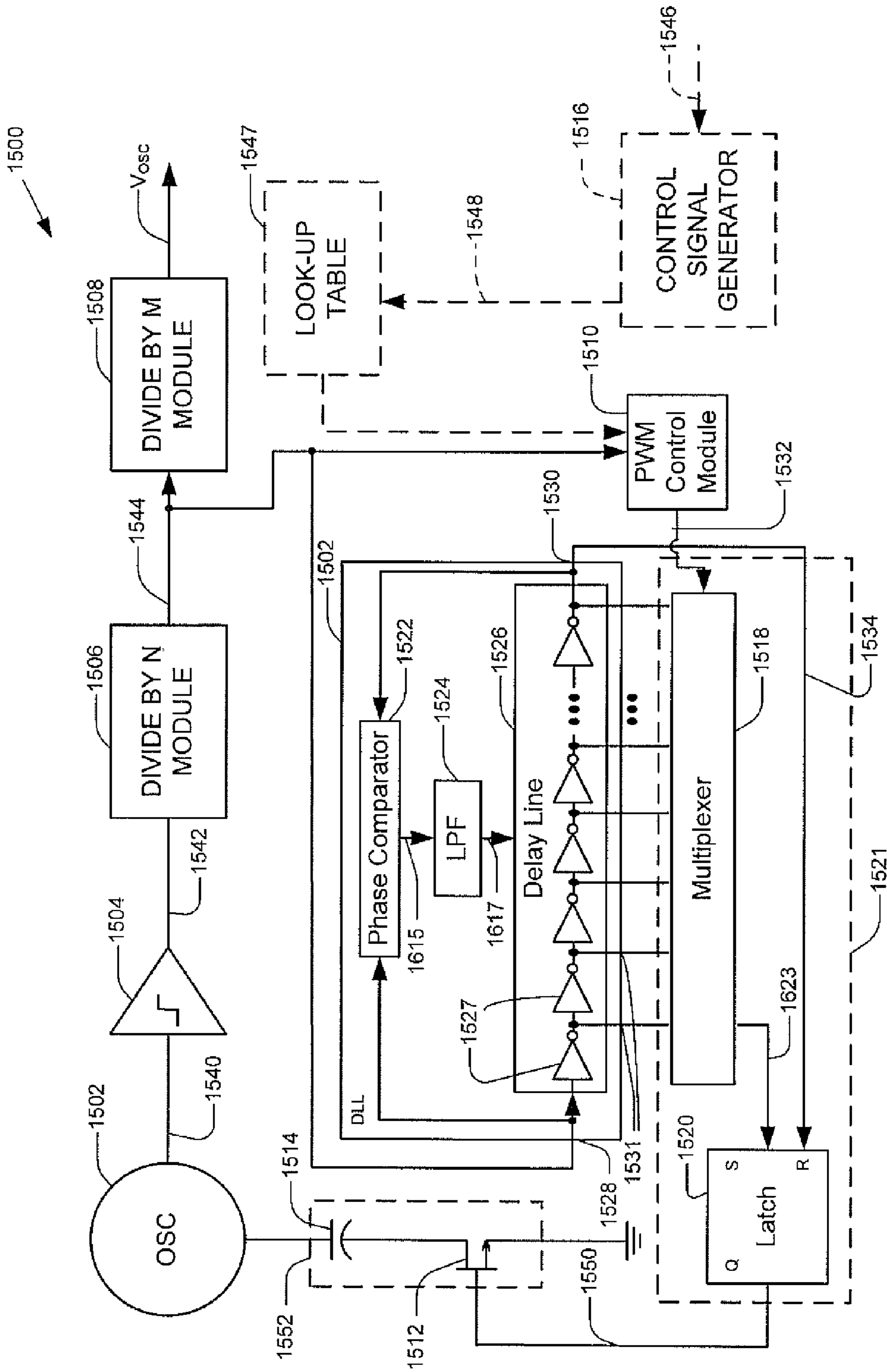
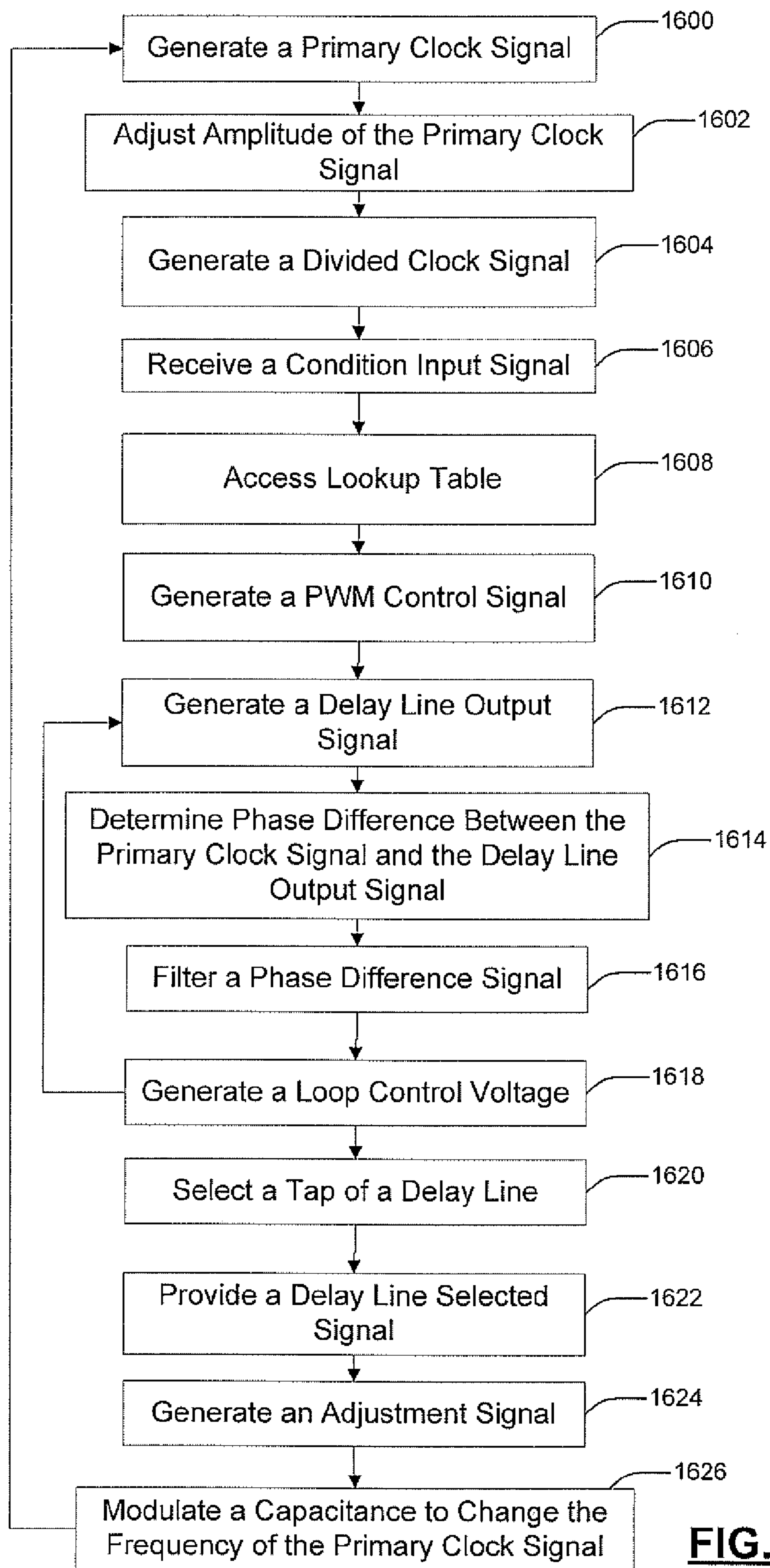


FIG. 14



**FIG. 15**

## VARIABLE CAPACITANCE WITH DELAY LOCK LOOP

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 12/180,853, filed Jul. 28, 2008, which claims the benefit of U.S. Provisional Application No. 61/024,711, filed Jan. 30, 2008, and is a continuation-in-part of U.S. patent application Ser. No. 12/114,479, filed on May 2, 2008, which is a continuation of U.S. patent application Ser. No. 11/242,230 (now U.S. Pat. No. 7,375,597), filed on Oct. 3, 2005, which claims the benefit of U.S. Provisional Application No. 60/704,280, filed on Aug. 1, 2005, and U.S. Provisional Application No. 60/722,732, filed on Sep. 30, 2005. The disclosures of the applications referenced above are incorporated herein by reference.

### FIELD

The present disclosure relates generally to electronic circuit tuning, and more particularly to pulse-width modulating capacitors to achieve low-noise, fine-frequency tuning.

### BACKGROUND

The background description provided herein is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

Frequency responses of electronic circuits are tuned in various applications, such as wired or wireless switches, controllers, transceivers, filters, power management units, data storage units, etc. Current techniques used to tune a frequency response have limited resolution and limited noise minimization control.

In addition, some tuning circuits tend to require additional terminals and system board space. For example, tuning circuits with crystal oscillators are used for high accuracy and low temperature drift tuning applications. A crystal oscillator, when used as a separate stand-alone device, is coupled to one or more pins of an integrated circuit and consumes system board space.

To save system board space, varactor diodes may be used and included in an integrated circuit. However, when capacitance of a varactor diode is tuned, such as by applying an analog control voltage in an open loop manner, noise problems result. Although current of the integrated circuit can be increased in order to reduce the noise, increased current results in increased power consumption. Increased power consumption decreases the working life of battery powered electronic systems.

Digitally adjusted capacitors, such as capacitors that are connected or disconnected using a switch, can be used to reduce noise in a tuning circuit. Digitally adjusted capacitors are typically either equally or binarily weighted. When equally weighted, a large number of capacitors and corresponding switches provide tuning with a large tuning range and a fine resolution. Where binarily weighted, capacitors with small capacitance values are limited in size by parasitic capacitances of the switches. Capacitors with large capacitance values are limited by available die area.

## SUMMARY

In one embodiment, an integrated circuit is provided and includes a delay lock loop (DLL) circuit. The DLL circuit generates incremental delay line signals and a delay line output signal based on a received clock signal. A pulse-width modulation (PWM) control module generates a PWM control signal. A variable capacitance circuit is controlled based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In other features, the variable capacitance circuit includes a capacitance and a switch that enables current flow to the capacitance based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In other features, the integrated circuit includes a multiplexer that generates a selected delay line signal based on the PWM control signal and one of the incremental delay line signals. In other features, the variable capacitance circuit is controlled based on the selected delay line signal and the delay line output signal.

In other features, the integrated circuit includes a latch that enables current flow to the variable capacitance circuit based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In still other features, the integrated circuit includes a latch that controls charging of the variable capacitance circuit based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In other features, the integrated circuit includes a multiplexer that generates a selected delay line signal based on the PWM control signal and one of the incremental delay line signals. A latch generates an adjustment signal based on the selected delay line signal and the delay line output signal. A switch enables current flow to the variable capacitance circuit based on the adjustment signal.

In yet other features, the PWM control module generates the PWM control signal based on a condition signal. In other features, the condition signal is generated based on a measurement of one of an environment and a process.

In other features, the DLL circuit includes a phase detector that detects the difference in phase between the received clock signal and the delay line output signal. The delay line output signal is generated based on the phase difference. In other features, the DLL circuit includes a filter that generates a filtered difference signal based on the phase difference. The delay line output signal is generated based on the filtered difference signal.

In further features, the integrated circuit includes a calibration control module that generates a calibration control signal based on the received clock signal. The PWM control module generates the PWM control signal based on the calibration control signal. In other features, the calibration control module generates the calibration control signal based on a reference clock signal. In other features, the calibration control module generates the calibration control signal based on a temperature signal.

In still other features, the integrated circuit includes a calibration control module that generates a calibration control signal based on a temperature signal. The pulse-width modulation circuit generates the PWM control signal based on the calibration control signal.

In other features, the integrated circuit includes a divide-by-N module that divides the received clock signal to generate a divided clock signal, where N is an integer greater than 0. The DLL circuit generates the incremental delay line signals and the delay line output signal based on the divided clock signal.

In yet other features, the integrated circuit includes a divide-by-N module that divides the received clock signal to generate a divided clock signal, where N is an integer greater than 0. The PWM control module generates the PWM control signal based on the divided clock signal. In other features, the PWM control module generates the PWM control signal based on the divided clock signal and a received condition signal. In other features, the condition signal is generated based on a measurement of one of an environment and a process.

In further features, the PWM control module generates the PWM control signal based on entries in a lookup table. In other features, the PWM control module generates the PWM control signal based on temperature entries in the lookup table.

In other features, a method of operating an integrated circuit is provided and includes generating incremental delay line signals and a delay line output signal based on a received clock signal. A PWM control signal is generated. A variable capacitance circuit is controlled based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In other features, the method includes enabling current flow to a capacitance of the variable capacitance circuit based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In still other features, the method includes generating a selected delay line signal based on the PWM control signal and one of the incremental delay line signals. In other features, the method includes controlling the variable capacitance circuit based on the selected delay line signal and the delay line output signal.

In other features, the method includes enabling current flow to the variable capacitance circuit based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In yet other features, the method includes charging the variable capacitance circuit based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In other features, the method includes generating a selected delay line signal based on the PWM control signal and one of the incremental delay line signals. An adjustment signal is generated based on the selected delay line signal and the delay line output signal. Current flow is enabled to the variable capacitance circuit based on the adjustment signal.

In other features, the method includes generating the PWM control signal based on a condition signal. In other features, the condition signal is generated based on a measurement of one of an environment and a process.

In further features, the method includes detecting difference in phase between the received clock signal and the delay line output signal. The delay line output signal is generated based on the phase difference.

In other features, the method includes generating a filtered difference signal based on the phase difference. The delay line output signal is generated based on the filtered difference signal.

In other features, the method includes generating a calibration control signal based on the received clock signal. The PWM control signal is generated based on the calibration control signal. In other features, the calibration control signal is generated based on a reference clock signal. In other features, the calibration control signal is generated based on a temperature signal.

In still other features, the method includes generating a calibration control signal based on a temperature signal. The PWM control signal is generated based on the calibration control signal.

In other features, the method includes dividing the received clock signal to generate a divided clock signal via a divide-by-N module, where N is an integer greater than 0. The incremental delay line signals and the delay line output signal are generated based on the divided clock signal.

In yet other features, the method includes dividing the received clock signal to generate a divided clock signal via a divide-by-N module, where N is an integer greater than 0. The PWM control signal is generated based on the divided clock signal.

In other features, the PWM control signal is generated based on the divided clock signal and a received condition signal. In other features, the condition signal is generated based on a measurement of one of an environment and a process. In other features, the PWM control signal is generated based on entries in a lookup table. In other features, the PWM control signal is generated based on temperature entries in the lookup table.

In further features, an integrated circuit is provided and includes DLL means for generating incremental delay line signals and a delay line output signal based on a received clock signal. Pulse-width modulation means generates a PWM control signal. Variable capacitance means provides a variable capacitance that is controlled based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In other features, the variable capacitance means includes capacitance means for providing a capacitance. Switching means enables current flow to the capacitance based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In still other features, the integrated circuit includes multiplexing means for generating a selected delay line signal based on the PWM control signal and one of the incremental delay line signals. In other features, the variable capacitance means is controlled based on the selected delay line signal and the delay line output signal.

In other features, the integrated circuit includes latching means for enabling current flow to the variable capacitance means based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In yet other features, the integrated circuit includes latching means for controlling charging of the variable capacitance means based on the delay line output signal, the PWM control signal, and one of the incremental delay line signals.

In other features, the integrated circuit includes multiplexing means for generating a selected delay line signal based on the PWM control signal and one of the incremental delay line signals. Latching means generates an adjustment signal based on the selected delay line signal and the delay line output signal. Switching means enables current flow to the variable capacitance means based on the adjustment signal.

In other features, the pulse-width modulation means generates the PWM control signal based on a condition signal. In other features, the condition signal is generated based on a measurement of one of an environment and a process.

In further features, the DLL means includes phase detection means for detecting the difference in phase between the received clock signal and the delay line output signal. The delay line output signal is generated based on the phase difference.

## 5

In other features, the DLL means includes filtering means for generating a filtered difference signal based on the phase difference. The delay line output signal is generated based on the filtered difference signal.

In other features, the integrated circuit includes calibration means for generating a calibration control signal based on the received clock signal. The pulse-width modulation means generates the PWM control signal based on the calibration control signal.

In other features, the calibration control means generates the calibration control signal based on a reference clock signal. In other features, the calibration control means generates the calibration control signal based on a temperature signal.

In still other features, the integrated circuit includes calibration means for generating a calibration control signal based on a temperature signal. The pulse-width modulation means generates the PWM control signal based on the calibration control signal.

In yet other features, the integrated circuit includes divide-by-N means for dividing the received clock signal to generate a divided clock signal, where N is an integer greater than 0. The DLL means generates the incremental delay line signals and the delay line output signal based on the divided clock signal.

In other features, the integrated circuit includes divide-by-N means for dividing the received clock signal to generate a divided clock signal, where N is an integer greater than 0. The pulse-width modulation means generates the PWM control signal based on the divided clock signal.

In other features, the pulse-width modulation means generates the PWM control signal based on the divided clock signal and a received condition signal. In other features, the condition signal is generated based on a measurement of one of an environment and a process.

In other features, the pulse-width modulation means generates the PWM control signal based on entries in a lookup table. In other features, the pulse-width modulation means generates the PWM control signal based on temperature entries in the lookup table.

In still other features, the systems and methods described above are implemented by a computer program executed by one or more processors. The computer program can reside on a computer readable medium such as but not limited to memory, non-volatile data storage and/or other suitable tangible storage mediums.

Further areas of applicability of the present disclosure will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred embodiment of the disclosure, are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

## BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

FIG. 1 is a schematic of a circuit having a frequency characteristic tuned by a pulse-width modulated capacitor according to an embodiment of the present disclosure;

FIG. 2 is a block diagram of a free-running oscillation circuit according to an embodiment of the present disclosure;

FIG. 3 is a block diagram illustrating the free-running oscillation circuit of FIG. 2 undergoing calibration;

FIG. 4A is a flowchart of a method of calibrating the free-running oscillation circuit of FIG. 2, and FIG. 4B is a

## 6

flowchart of a method of calibrating a circuit according to an embodiment of the present disclosure;

FIG. 5 is a more detailed block diagram of a free-running oscillation circuit according to an embodiment of the present disclosure;

FIG. 6 is a flowchart illustrating the operation of the free-running oscillation circuit of FIG. 5;

FIG. 7 is a schematic of an oscillator that may be used as the oscillator 510 in the free-running oscillation circuit of FIG. 5 or as an oscillator in other embodiments of the present disclosure;

FIG. 8 illustrates a control signal generator and pulse-width modulator that may be used as the control signal generator and pulse-width modulator of FIG. 5 or as a control signal generator and pulse-width modulator in other embodiments of the present disclosure;

FIG. 9 is a timing diagram illustrating the operation of the pulse-width modulator of FIG. 8; and

FIG. 10A is a functional block diagram of a hard disk drive;

FIG. 10B is a functional block diagram of a DVD drive;

FIG. 10C is a functional block diagram of a high definition television;

FIG. 10D is a functional block diagram of a vehicle control system;

FIG. 10E is a functional block diagram of a cellular phone;

FIG. 10F is a functional block diagram of a set top box;

FIG. 10G is a functional block diagram of a media player;

FIG. 10H is a functional block diagram of a VoIP player;

FIG. 11 is a block diagram of a free-running oscillation circuit incorporating a delay lock loop (DLL) circuit according to an embodiment of the present disclosure;

FIG. 12 is a block diagram illustrating the free-running oscillation circuit of FIG. 11 undergoing calibration;

FIG. 13 is a flowchart illustrating a method of calibrating the free-running oscillation circuit of FIG. 12 according to another embodiment of the present disclosure;

FIG. 14 is a block diagram of a free-running oscillation circuit incorporating a DLL circuit according to another embodiment of the present disclosure; and

FIG. 15 is a data flow diagram illustrating operation of the free-running oscillation circuit of FIG. 14 according to another embodiment of the present disclosure.

## DETAILED DESCRIPTION

The following description is merely exemplary in nature and is in no way intended to limit the disclosure, its application, or uses. For purposes of clarity, the same reference numbers will be used in the drawings to identify similar elements. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A or B or C), using a non-exclusive logical or. It should be understood that steps within a method may be executed in different order without altering the principles of the present disclosure.

As used herein, the term module refers to an Application Specific Integrated Circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group) and memory that execute one or more software or firmware programs, a combinational logic circuit, and/or other suitable components that provide the described functionality.

Referring to FIG. 1 is a schematic of a circuit having a frequency response or characteristic tuned by a pulse-width modulated capacitor according to an embodiment of the present invention. This figure includes a circuit 110, transistor M1 120, and capacitor C1 130. The circuit 110 has a frequency response or characteristic that is at least partially determined by the effective capacitance value of the capacitor



C1 130. The circuit 110, transistor 120, and capacitor 130 may be included on an integrated circuit. This figure, as with the other included figures, is shown for exemplary purposes and does not limit either the possible embodiments of the present invention or the claims.

The adjust signal on line 122 adjusts or controls the impedance of transistor M1 120. When the level of the adjust signal on line 122 is high, and transistor M1 120 is on and connects capacitor C1 130 to ground, in effect connecting capacitor C1 130 to the circuit 110. When the adjust signal on line 122 is low, the impedance of transistor M1 120 is high, allowing capacitor C1 130 to float, effectively disconnecting the capacitor C1 130 from the circuit 110. When this capacitor is connected to ground, it is at least partially responsible for determining a frequency characteristic of the circuit 110. Conversely, when the capacitor C1 130 is floating, it has a reduced effect on this frequency response or characteristic.

However, when the capacitor C1 130 is floating it is not completely removed or disconnected. Transistor M1 120 includes parasitic capacitances, notably the drain-to-gate capacitance and the capacitance of the drain-to-bulk diode, which remains in series with capacitor C1 130 when transistor M1 120 is off. These parasitic capacitances limit the minimum practical size of C1 130. This in turn limits the resolution with which the frequency characteristic of the circuit 110 can be tuned.

Accordingly, embodiments of the present invention adjust the size of capacitor C1 130 with a finer resolution by applying a switching signal having a variable duty cycle, specifically the adjust signal on line 122. By varying the duty cycle of the adjust signal on line 122, the capacitor C1 130 is connected to the circuit 110 part of the time, and disconnected from the circuit 110 for the remainder. In this way, a duty cycle adjustment can be used to vary the effective size of capacitor C1 130. That is, as the duty cycle increases and device M1 120 is on for a greater portion of time, the effective size of capacitor C1 130 is increased, while as the duty cycle is decreased, device M1 120 conducts or is on for a shorter portion and the effective size of C1 130 is thereby reduced.

Thus, a frequency response or characteristic of the circuit 110 can be adjusted by varying the duty cycle of the adjust signal on line 122. However, it should be noted that changes in the frequency of the adjust signal on line 122 by themselves do not have a first-order effect on the effective capacitance provided by the capacitor C1 130.

During operation when M1 120 is on, the voltage V2 on line 134 (the drain of M1 120) is near ground. When the adjust signal on line 122 switches low thereby shutting off M1 120, the voltage V2 on line 134 is allowed to float. Accordingly, the voltage V2 on line 134 tracks changes in the voltage V1 on line 132. Later, when the adjust signal on line 122 returns high and M1 120 conducts, the voltage V2 on line 134 is again forced to ground. If the voltage V2 on line 134 has floated from ground when device M1 120 turns on, charge is injected through C1 130 into the circuit 110. This charge injection should be accounted for in the design of the circuit 110 and the timing of the adjust signal on line 122. It should also be noted that the drain-to-bulk diode might turn on and clamp the voltage V2 on line 134 when the capacitor C1 130 is allowed to float, specifically when the voltage V2 on line 134 floats below ground. This clamping can be minimized by ensuring that the signal swing at V1 132 does not exceed a few hundred millivolts.

In a specific embodiment of the present invention, the circuit 110 is an oscillator that provides an oscillatory signal at a frequency that is determined at least in part by the effective value of the capacitor C1 130. In this embodiment, the

adjust signal on line 122 is opened and closed at a frequency that is a sub-harmonic of the frequency of the oscillator. Accordingly, each time the transistor M1 120 closes or begins to conduct, the voltage V2 on line 134 is near ground, thus limiting the charge injection back into the oscillator.

In this exemplary figure, the circuit 110 receives an input signal on line 112 and provides an output on line 114. In various embodiments of the present invention, there is no input signal 112, for example where the circuit 110 is an oscillator as described above. The input and output signals may use single-ended or differential signaling techniques. Typically, lines in this and the other figures may be one line, or a group of lines, such as a bus.

The capacitor C1 130 may be in parallel or in series with one or more other capacitors that may or may not be connected to switches. The capacitor C1 130 may be a metal-sinker capacitor, a metal-to-metal capacitor, or other type of capacitor. It may be one capacitor, or a combination of more than one individual capacitor. The transistor M1 120 may be an n-channel MOS device as shown. Alternately it may be a p-channel MOS device, bipolar device, HFET, HBT, MES-FET, or other type of transistor. In other embodiments of the present invention, the transistor M1 120 may be replaced by another type of switch such as a pass or tri-state gate. Also, in some embodiments the switch and the capacitor may be combined into a single composite structure. While these figures show a switch transistor coupled between a capacitor and ground, in various embodiments, the switch may be between the capacitor and the circuit, between the capacitor and another node, such as a bias voltage or a supply voltage, or the switch and capacitor may be take on other arrangements.

The circuit 110 may be an oscillator as previously described, a filter, or other circuit where a variable frequency response or characteristic is desired. One example of an oscillator incorporating an embodiment of the present invention is shown in the next figure.

FIG. 2 is a block diagram of a free-running oscillation circuit according to an embodiment of the present invention. This figure includes an oscillator 210, pulse-width modulator 220, transistor M1 230, and capacitor C1 240. The oscillator 210 generates a clock signal on line 212. The clock signal has a frequency that is determined at least partially by the effective capacitance value provided by the capacitor C1 240 and transistor M1 230.

A condition signal is received on line 222 by the pulse-width modulator 220. This condition signal may be either a current or a voltage that is provided or generated in response to an environmental, process, or other condition or combination thereof. For example, the condition signal on line 222 may be in response to a temperature, power supply voltage, or other environmental condition. Alternately, the condition signal on line 222 may be in response to a process variation occurring during the manufacture of an integrated circuit that includes one or more of the circuits in this figure. In other embodiments, the condition signal on line 222 may be a control setting, for example, a voltage provided by a potentiometer. The condition signal 222 may be proportional to the condition itself or it may have another relationship to the condition. For example, the condition signal may be a current or a voltage that is proportional to absolute temperature.

The pulse-width modulator 220 converts the condition signal on line 222 into the adjust signal on line 224. Specifically, the pulse-width modulation circuit 220 varies the duty cycle of the adjust signal on line 224 as a function of the condition signal received on line 222.

The transistor M1 230 turns on and off under control of the level of the adjust signal on line 224, thus alternately connect-

ing and disconnecting the capacitor C1 240 from the oscillator 210. The longer capacitor C1 240 is connected to the oscillator 210, the greater the effective capacitance value of the capacitor C1 240. While only one capacitor C1 240 and corresponding transistor M1 230 are shown, practical circuits typically include several such capacitor-transistor combinations in parallel or in series with each other, the transistors (or other switches) under control of various adjust signals.

Again, in a specific embodiment of the present invention, the adjust signal on line 224 is a sub-harmonic of the clock frequency on line 212. In this embodiment, the clock signal on line 212 clocks the pulse width modulation circuit 220. In one embodiment, the nominal frequency of the oscillator 210 is 1.280 GHz. This frequency is divided by a factor of four to 320 MHz, which is further divided by 32, resulting in a fundamental frequency of 10 MHz for the adjust signal on line 224. The duty cycle of this 10 MHz signal is then varied and provided as the adjust signal on line 224.

The relationship between the condition signal on line 222 and the adjust signal on line 224 may be different in various embodiments of the present invention. That is, the pulse width modulation circuit 220 may be configured such that the frequency of the clock signal on line 212 tracks in the condition signal on line 222. Alternately, other relationships are possible. For example, the pulse width modulation circuit 220 may be configured to provide a frequency for the clock signal on line 212 that is stable over changes in the condition that is measured to generate the condition signal on line 222.

A specific embodiment of the present invention provides an oscillator having a clock signal with a frequency that is stable over temperature. In order to achieve this, the oscillator first undergoes a calibration process. Examples of such a calibration process are shown in the next two figures.

FIG. 3 is a block diagram illustrating the free-running oscillation circuit of FIG. 2 while it is undergoing calibration. This figure includes an oscillator 310, reference oscillator 320, calibration control circuit 330, programmable lookup table 340, transistor M1 350, capacitor C1 360, and pulse width modulator circuit 370. The frequency of oscillation of the oscillator 310 is determined at least in part by the effective capacitance value provided by the capacitor C1 360. Typically, the oscillator 310, transistor M1 350, and capacitor C1 360 are included on an integrated circuit, while the reference oscillator 320 is separate. The calibration control circuit 330 and lookup table 340 may or may not be included on the integrated circuit depending on the exact implementation.

The reference oscillator 320 may be a crystal oscillator or other periodic source. Alternately, it may be such a source in conjunction with one or more frequency multipliers or dividers. The calibration control circuit 330 includes a frequency detector that compares the frequency of the reference clock signal on line 322 to the frequency of the clock signal on line 312. From this information, the calibration control circuit 330 provides a control signal on line 332.

The calibration control circuit 330 varies the value of the control signal on line 332 in a manner depending on the relative frequencies of these input signals. When the frequency of the clock signal on line 312 is tuned within an acceptable margin of error to the frequency of the reference clock signal on line 322, the control signal on line 332, or other data corresponding to the control signal on line 332, is stored in the lookup table 340 along with the condition measurement. This process may be repeated at several condition values or states, and for one or more different conditions.

Once a number of control signal values and their corresponding condition measurements are stored in the lookup table 340, the data can be read out and further processed,

though in other embodiments of the present invention, data is processed when determined without first being stored in a lookup table 340. In one embodiment of the present invention, a best-fit curve is generated based on the data. In a specific embodiment, this curve is described by a second-order polynomial, though in other embodiments of the present invention it may be a different type of curve having a different order. Alternately, the curve may be predefined where the data used to shift the curve, not to define it. Other variations or combinations can also be used. After the data is fit to a curve, several more control signal data points can be interpolated between the measured data points.

A processor that is external to the integrated circuit can perform the curve fitting and interpolation. For example, a processor that is part of a test or manufacturing system can perform either or both of these functions. Alternately, an on-chip processor can do either or both of these functions, or they may be shared between on-chip and off-chip processors.

The interpolated control signal values (or data corresponding to control signal values) can be stored in a lookup table or other memory. The data can be addressed by the corresponding condition measurement value. This lookup table can be the same lookup table 340 as is used to store condition measurements and control signal values before curve fitting is done. Alternately, another lookup table can be used. The lookup table or other memory used to store interpolated data is typically on-chip; though in other embodiments it can be off-chip.

In a specific embodiment of the present invention, an on-chip heating circuit is used to vary the temperature of an integrated circuit that includes a circuit to be calibrated. This heating circuit dissipates a variable amount of power in order to adjust die temperature; die temperature being the measured condition. One such heating circuit can be found in copending U.S. patent application Ser. No. 11/243,017, titled "On-Die Heating Circuit and Control Loop for Rapid Heating of the Die," by Jody Greenberg and Sehat Sutardja, filed Sep. 3, 2005, which is incorporated by reference.

The control signal values required for the frequency of the oscillator 310 to match the frequency of the reference oscillator 320 are stored for a number of temperatures. The temperature can be measured, or the temperature can be inferred given a specific level of power dissipation in the heater circuit. Since each temperature measurement costs money, embodiments of the present invention typically limit the number of temperature data points taken. For example, in one embodiment, two temperature data points are taken. An expected curve is used, where the two data points are used to shift and adjust the curve. In another embodiment of the present invention, five data points are used, and a second-order polynomial curve is fit to the data. In other embodiments, other curve-fitting techniques and other number of data points can be used.

From this curve, a larger number of data points can be interpolated. For example, in the specific embodiment, temperature is converted from an analog PTAT voltage to an 8-bit address using an 8-bit analog-to-digital converter. Accordingly, 256 data points are interpolated and stored in a memory or lookup table that is addressed by the digital conversion of the temperature. In other embodiments, converters having other resolutions and memories having other numbers of addressable locations can be used.

In operation, the temperature is measured, converted to a digital signal, and used to address a control signal value. The control signal value is used to generate a pulse-width modulated adjust signal, which in turn varies a capacitor value that tunes the oscillator to the desired frequency.

## 11

FIG. 4A is a flowchart of a method of calibrating the free-running oscillation circuit of FIG. 2. A condition signal corresponding to an environmental, process, or other condition is received in step 400. In step 405, a reference clock signal is received. In step 410, an oscillator clock frequency is received. The frequency of the reference clock is compared to the frequency of the oscillator in step 415.

In step 420, it is determined whether the oscillator is operating at the correct frequency. Specifically, it is determined whether the frequency of the oscillator clock signal is within a margin of error of the frequency of the reference clock signal. If it is, the control signal value, or information corresponding to the control signal, can be stored with the measured condition value in step 445.

If it is not, the comparison is used to generate a control signal in step 425. The control signal is used to generate an adjust signal having a variable duty cycle in step 430. In step 435, the adjust signal is used to pulse-width modulate or vary a capacitance. The modulated capacitance changes the oscillator frequency in step 440. The oscillator clock, with its new frequency, can then be received and compared to the reference clock.

When data is taken at each of the desired temperatures, the condition values and corresponding data can be read in step 450. More data points can be interpolated, for example by use of curve fitting, in step 455. The interpolated control signal values can be stored in step 460.

While this calibration technique is well suited to calibrating a free-running oscillator, it may be used for other circuits as well. One method that is applicable to many other circuits is shown in the following figure.

FIG. 4B is a flowchart of a method of calibrating a circuit according to an embodiment of the present invention. In step 480, a condition is set and measured. For example, a temperature may be set using a heating circuit as described above. In step 482, a control signal that is required to achieve a desired outcome at the set condition is determined. In step 484, the condition measurement and required control signal data is stored. This data may be stored in an on-chip, or off-chip memory, FIFO, lookup table, registers, or other storage locations. Alternately, the data may be processed or further used in real-time without being stored. Alternately, the condition measurement values may be inferred, and the required control signal data stored at locations identified by those inferred values.

In step 486, it is determined whether data has been taken at the last condition. If it hasn't, the condition is set and measured again in step 480. When data has been taken at each desired condition, the stored condition measurements and required control signal data can be read in step 488. In step 490, additional control signal data points can be interpolated. This may be done by fitting the stored data to a curve, or by other method. One or more processors can perform this curve fitting and interpolation, and these processors can be on-chip or off-chip. Alternately, on-chip and off-chip circuits or processors can share the processing workload. In step 492, the interpolated control signal data points are stored. Typically, this data is stored on-chip, though it may be stored off-chip in various embodiments of the present invention. For example, the data may be stored in an on-chip lookup table or other memory, where address locations are identified by values of the condition signal.

Further refinements to the oscillator circuit shown in FIG. 2 may be desirable in some embodiments of the present invention. For example, a hysteresis buffer can be used to clean up the oscillator output signal. Also, various frequency

## 12

dividers may be used such that a desired clock frequency is realized. Examples are described in the following two figures.

FIG. 5 is a more detailed block diagram of a free-running oscillation circuit according to an embodiment of the present invention. This circuit includes an oscillator 510, buffer 520, dividers 530 and 540, pulse-width modulation circuit 550, transistor M1 560, capacitor C1 570, and control signal generator 580. The effective capacitance of the capacitor C1 570 at least partially determines a frequency response or characteristic of the oscillator 510, for examples its oscillation frequency. While only one capacitor C1 570 and corresponding transistor M1 560 is shown for simplicity, typical embodiments of the present invention included several such combinations in series or parallel controlled by various adjust signals.

The oscillator 510 provides an output oscillation signal to the buffer 520. The buffer 520 gains and sharpens the edges of the output signal provided by the oscillator 510, which is typically a low-amplitude sinusoid. The buffer 520 may also include hysteresis to provide a substantially glitch free output.

The output of the buffer 520 is received by a divider circuit 530, which divides the frequency provided by the oscillator by a factor of "N." This signal can further be divided by divider 540, which in this example divides the frequency by a factor of "M" to provide a signal Vosc on line 542. In other embodiments, other frequency dividers and multipliers may be used. These dividers may also be programmable.

The control signal generator circuit 580 receives a condition signal on line 582. Again, this signal may be derived by the measurement of an environmental, process, or other type of parameter. The control signal generator circuit 580 provides a control signal on line 552 to the pulse-width modulator circuit 550. The pulse width modulator circuit 550 provides an adjust signal on line 554 to the oscillator circuit. This signal has a duty cycle that is modulated as a function of the condition signal received on line 552.

The adjust signal on line 554 controls the impedance of transistor M1 560, which connects and disconnects capacitor C1 570 from the oscillator 510. Changes in the duty cycle of the adjust signal on line 554 varies the effective capacitance of capacitor C1 570 seen by the oscillator 510. This in turn varies its oscillation frequency, and thus the frequency of the output signal Vosc on line 542.

FIG. 6 is a flowchart illustrating the operation of the free-running oscillation circuit of FIG. 5. An oscillation signal is generated in step 610. In step 620, this oscillation signal is gained. This has the effect of sharpening the edges and increasing the amplitude of the oscillation signal. In step 630, the frequency of the oscillation signal is divided. In step 640, a measurement of a condition is received. As before, the condition may be an environmental, process, or other type of condition. The measurement received may be a voltage or current that is related to the condition. For example, a voltage proportional to absolute temperature may be received.

In step 650, a lookup table entry is found using the measurement of the condition. In step 660, an adjustment signal is generated using the lookup table entry and the divided-gained oscillation signal. The adjustment signal is used to set the frequency of the oscillation signal in active 670.

The entries in the lookup table may be such that the resulting oscillation frequency remains constant over temperature. Alternately, they may be such that the resulting oscillation frequency has some relationship to temperature. In other embodiments, other conditions besides temperature may be used in finding entries in the lookup table. Further, more than one condition may be used by various embodiments of the

present invention. In other embodiments, other memories or storage circuits can be used instead of a lookup table.

FIG. 7 is a schematic of an oscillator that may be used as the oscillator 510 in the free-running oscillation circuit of FIG. 5, or as an oscillator in other embodiments of the present invention. This figure includes a bias current generator 700, an oscillator core (or tank) including transistors M1A 710 and M2A 720, load (or tank) inductors L1 730 and L2 740, and pulse-width modulated capacitors C1 755, C2 765, and CN 775, as well as their corresponding transistors M1 750, M2 760, and MN 770. Only the pulse-width modulated capacitors connected to the drain of M2A 720 are shown: corresponding capacitors and transistors connected to the drain of transistor M1 710 are omitted for clarity. The gates of the omitted corresponding transistors can be driven by the same signals as transistors M1 750, M2 750, and MN 770, though they may be driven by other signals. Other capacitors that are not selectively coupled and decoupled from the oscillator core are also typically connected to the drains of M1A 710 and M2A 720. These capacitors have been omitted for clarity.

The frequency of oscillation of this circuit is determined by the values of the inductors and the effective capacitance values seen by those inductors. These capacitors may be connected or disconnected by their corresponding transistors on a steady-state basis, or they may be switched by a signal having a duty cycle under control of a pulse with modulation circuit.

In one embodiment of the present invention, there are 16 capacitors and corresponding transistors connected to the drain of M2A 720, and 16 other capacitors connected to the drain of M1A 710. These transistors can be equally weighted, and they can be switched under control of 4 bits that are thermally decoded into 16 adjust signals. The signals can have a duty cycle that is varied in increments of one thirty-second of the period of the adjust signals. In other embodiments, other numbers of capacitors may be used, and their values may be weighted in a different manner. For example, they may be binarily weighted, and four, eight, or thirty-two capacitors may be used. Further, the duty cycle may be varied in equal or unequal increments, and the number of increments may be more or less than 32. For example, the duty cycle may be varied in eighths, sixteenths, or sixty-fourths of the adjust signal period. Alternately, non-binary numbers may be used for any of these parameters.

In one exemplary embodiment of the present invention, a maximum frequency for the oscillation circuit is achieved when all capacitors remain disconnected by their corresponding transistors. The frequency of oscillation can be reduced by one quantum by applying an adjust signal having a minimum duty cycle to one transistor (or typically, one transistor connected to a capacitor that is connected to the drain of M1A 710 and one transistor connected to a capacitor that is connected to the drain of M2A 720). The frequency of oscillation can further be reduced by increasing this duty cycle, until the transistor remains on, that is, until its adjust signal has a duty cycle of one.

Further decreases in oscillator frequency are achieved by applying an adjust signal having a minimum duty cycle to a second transistor while the first transistor remains fully on and the remaining transistors remain off. Decreases in oscillator frequency can continue until all transistors remained fully on, at which point a minimum oscillation frequency is reached. The operation of one exemplary pulse-width modulator that provides signals such as these is shown in the next two figures.

FIG. 8 is a control signal generator and pulse-width modulator that may be used as the control signal generator and

pulse-width modulator of FIG. 5 or as a control signal generator and pulse-width modulator in other embodiments of the present invention. This figure includes a control signal generator made up of an analog-to-digital converter 810 and lookup table 820, and a pulse-width modulator made up of a counter 830 and decoder 840. In other embodiments of the present invention, other circuits can be used to implement the control signal generator and pulse-width modulator.

A condition signal is received on line 812 by the analog-to-digital converter 810. The analog-to-digital converter provides a digital word that is used to address the lookup table 820. The lookup table in turn provides a control signal to the counter 830 and decoder 840.

The control signal MSBs provided by the lookup table 820 on line 822 to the decoder 840 are decoded and provided as a number of adjust signals on lines 842. In one embodiment of the present invention, a thermometer decoder is used. A thermometer decoder decodes binarily weighted bits into a number of equally weighted bits. The control signal LSBs on line 824 provided to the counter 830 are used to control the duty cycle of at least one of the adjust signals on lines 842, as is shown in the timing diagram which follows.

FIG. 9 is a timing diagram illustrating the operation of the pulse-width modulator of FIG. 8. This figure includes a clock signal 910, adjust 1-3 signals 920, adjust 4 signal 930, and adjust 5-8 signals 940. The state of these signals represents one of 64 possible states for this exemplary embodiment of the present invention.

In this example, the adjust 1-3 signals 920 remain high, while adjust 5-8 signals 940 remain low. The adjust 4 signal 930 has a variable signal that has a duty cycle of three-eighths. That is, it is high for three cycles of the clock 910, and low for 5 clock cycles. In this embodiment, the eight adjust signals are decoded from three bits provided by lookup table, while the duty cycle is controlled by another three bits provided by lookup table. In a specific embodiment of the present invention, four bits are provided to the decoder for 16 adjust signals, and five bits are provided to the counter, for 32 possible duty cycles. In this embodiment, there are 512 possible signal states, that is, the capacitance of the tank circuit can be varied in 512 increments.

In this example, the effective capacitance can be reduced one quantum by changing the duty cycle to one-fourth, or increased one quantum by changing the duty cycle to one-half. In other embodiments, the period may be less than or more than 8 clock cycles, and more or less than eight adjust signals may be generated.

The capacitance seen by the oscillator when the adjust 4 signal 930 is high is greater than when the adjust 4 signal 930 is low. Accordingly, the oscillator tries to alternately decrease and increase its frequency. This would cause frequency modulation of the clock. However, if the clock is divided by the same ratio or integer multiple thereof as the pulse width modulated frequency then the frequency modulation is substantially cancelled.

Referring now to FIGS. 10A-10G, various exemplary implementations of the present invention are shown. Referring to FIG. 10A, the present invention may be embodied in a hard disk drive 1000. The present invention may implement either or both signal processing and/or control circuits, which are generally identified in FIG. 10A at 1002. In some implementations, signal processing and/or control circuit 1002 and/or other circuits (not shown) in HDD 1000 may process data, perform coding and/or encryption, perform calculations, and/or format data that is output to and/or received from a magnetic storage medium 1006.

15

HDD **1000** may communicate with a host device (not shown) such as a computer, mobile computing devices such as personal digital assistants, cellular phones, media or MP3 players and the like, and/or other devices via one or more wired or wireless communication links **1008**. HDD **1000** may be connected to memory **1009**, such as random access memory (RAM), a low latency nonvolatile memory such as flash memory, read only memory (ROM) and/or other suitable electronic data storage.

Referring now to FIG. **10B**, the present invention may be embodied in a digital versatile disc (DVD) drive **1010**. The present invention may implement either or both signal processing and/or control circuits, which are generally identified in FIG. **10B** at **1012**, and/or mass data storage **1018** of DVD drive **1010**. Signal processing and/or control circuit **1012** and/or other circuits (not shown) in DVD **1010** may process data, perform coding and/or encryption, perform calculations, and/or format data that is read from and/or data written to an optical storage medium **1016**. In some implementations, signal processing and/or control circuit **1012** and/or other circuits (not shown) in DVD **1010** can also perform other functions such as encoding and/or decoding and/or any other signal processing functions associated with a DVD drive.

DVD drive **1010** may communicate with an output device (not shown) such as a computer, television or other device via one or more wired or wireless communication links **1017**. DVD **1010** may communicate with mass data storage **1018** that stores data in a nonvolatile manner. Mass data storage **1018** may include a hard disk drive (HDD) such as that shown in FIG. **10A**. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8", DVD **1010** may be connected to memory **1019**, such as RAM, ROM, low latency nonvolatile memory such as flash memory, and/or other suitable electronic data storage.

Referring now to FIG. **10C**, the present invention may be embodied in a high definition television (HDTV) **1020**. The present invention may implement either or both signal processing and/or control circuits, which are generally identified in FIG. **10C** at **1022**, a WLAN interface and/or mass data storage of the HDTV **1020**. HDTV **1020** receives HDTV input signals in either a wired or wireless format and generates HDTV output signals for a display **1026**. In some implementations, signal processing circuit and/or control circuit **1022** and/or other circuits (not shown) of HDTV **1020** may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other type of HDTV processing that may be required.

HDTV **1020** may communicate with mass data storage **1027** that stores data in a nonvolatile manner such as optical and/or magnetic storage devices. At least one HDD may have the configuration shown in FIG. **10A** and/or at least one DVD may have the configuration shown in FIG. **10B**. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". HDTV **1020** may be connected to memory **1028** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. HDTV **1020** also may support connections with a WLAN via a WLAN network interface **1029**.

Referring now to FIG. **10D**, the present invention implements a control system of a vehicle **1030**, a WLAN interface and/or mass data storage of the vehicle control system. In some implementations, the present invention implements a powertrain control system **1032** that receives inputs from one or more sensors such as temperature sensors, pressure sensors, rotational sensors, airflow sensors and/or any other suit-

16

able sensors and/or that generates one or more output control signals such as engine operating parameters, transmission operating parameters, and/or other control signals.

The present invention may also be embodied in other control systems **1040** of vehicle **1030**. Control system **1040** may likewise receive signals from input sensors **1042** and/or output control signals to one or more output devices **1044**. In some implementations, control system **1040** may be part of an anti-lock braking system (ABS), a navigation system, a telematics system, a vehicle telematics system, a lane departure system, an adaptive cruise control system, a vehicle entertainment system such as a stereo, DVD, compact disc and the like. Still other implementations are contemplated.

Powertrain control system **1032** may communicate with mass data storage **1046** that stores data in a nonvolatile manner. Mass data storage **1046** may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. **10A** and/or at least one DVD may have the configuration shown in FIG. **10B**. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". Powertrain control system **1032** may be connected to memory **1047** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. Powertrain control system **1032** also may support connections with a WLAN via a WLAN network interface **1048**. The control system **1040** may also include mass data storage, memory and/or a WLAN interface (all not shown).

Referring now to FIG. **10E**, the present invention may be embodied in a cellular phone **1050** that may include a cellular antenna **1051**. The present invention may implement either or both signal processing and/or control circuits, which are generally identified in FIG. **10E** at **1052**, a WLAN interface and/or mass data storage of the cellular phone **1050**. In some implementations, cellular phone **1050** includes a microphone **1056**, an audio output **1058** such as a speaker and/or audio output jack, a display **1060** and/or an input device **1062** such as a keypad, pointing device, voice actuation and/or other input device. Signal processing and/or control circuits **1052** and/or other circuits (not shown) in cellular phone **1050** may process data, perform coding and/or encryption, perform calculations, format data and/or perform other cellular phone functions.

Cellular phone **1050** may communicate with mass data storage **1064** that stores data in a nonvolatile manner such as optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. **10A** and/or at least one DVD may have the configuration shown in FIG. **10B**. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". Cellular phone **1050** may be connected to memory **1066** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. Cellular phone **1050** also may support connections with a WLAN via a WLAN network interface **1068**.

Referring now to FIG. **10F**, the present invention may be embodied in a set top box **1080**. The present invention may implement either or both signal processing and/or control circuits, which are generally identified in FIG. **10F** at **1084**, a WLAN interface and/or mass data storage of the set top box **1080**. Set top box **1080** receives signals from a source such as a broadband source and outputs standard and/or high definition audio/video signals suitable for a display **1088** such as a television and/or monitor and/or other video and/or audio output devices. Signal processing and/or control circuits **1084**

and/or other circuits (not shown) of the set top box **1080** may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other set top box function.

Set top box **1080** may communicate with mass data storage **1090** that stores data in a nonvolatile manner. Mass data storage **1090** may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. **10A** and/or at least one DVD may have the configuration shown in FIG. **10B**. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". Set top box **1080** may be connected to memory **1094** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. Set top box **1080** also may support connections with a WLAN via a WLAN network interface **1096**.

Referring now to FIG. **10G**, the present invention may be embodied in a media player **1072**. The present invention may implement either or both signal processing and/or control circuits, which are generally identified in FIG. **10G** at **1071**, a WLAN interface and/or mass data storage of the media player **1072**. In some implementations, media player **1072** includes a display **1076** and/or a user input **1077** such as a keypad, touchpad and the like. In some implementations, media player **1072** may employ a graphical user interface (GUI) that typically employs menus, drop down menus, icons and/or a point-and-click interface via display **1076** and/or user input **1077**. Media player **1072** further includes an audio output **1075** such as a speaker and/or audio output jack. Signal processing and/or control circuits **1071** and/or other circuits (not shown) of media player **1072** may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other media player function.

Media player **1072** may communicate with mass data storage **1070** that stores data such as compressed audio and/or video content in a nonvolatile manner. In some implementations, the compressed audio files include files that are compliant with MP3 format or other suitable compressed audio and/or video formats. The mass data storage may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. **10A** and/or at least one DVD may have the configuration shown in FIG. **10B**. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". Media player **1072** may be connected to memory **1073** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. Media player **1072** also may support connections with a WLAN via a WLAN network interface **1074**.

Referring to FIG. **10H**, the present invention may be embodied in a Voice over Internet Protocol (VoIP) phone **1083** that may include an antenna **1039**. The present invention may implement either or both signal processing and/or control circuits, which are generally identified in FIG. **10H** at **1082**, a wireless interface and/or mass data storage of the VoIP phone **1083**. In some implementations, VoIP phone **1083** includes, in part, a microphone **1087**, an audio output **1089** such as a speaker and/or audio output jack, a display monitor **1091**, an input device **1092** such as a keypad, pointing device, voice actuation and/or other input devices, and a Wireless Fidelity (Wi-Fi) communication module **1086**. Signal processing and/or control circuits **1082** and/or other circuits (not shown) in VoIP phone **1083** may process data, perform coding and/or encryption, perform calculations, format data and/or perform other VoIP phone functions.

VoIP phone **1083** may communicate with mass data storage **502** that stores data in a nonvolatile manner such as optical and/or magnetic storage devices, for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. **10A** and/or at least one DVD may have the configuration shown in FIG. **10B**. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". VoIP phone **1083** may be connected to memory **1085**, which may be a RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. VoIP phone **1083** is configured to establish communications link with a VoIP network (not shown) via Wi-Fi communication module **1086**. Still other implementations in addition to those described above are contemplated.

Referring to FIG. **11**, a block diagram of a free-running oscillation circuit **1300** incorporating a DLL circuit **1302** is shown. The free-running oscillation circuit **1300** is similar to the free-running oscillation circuit of FIG. **3** in that it includes an oscillator **1304**, a pulse-width modulation (PWM) control module **1306**, a transistor **1308**, a capacitor **1310**. The free-running oscillation circuit **1300** also includes the DLL circuit **1302**, as well as a multiplexer **1312** and a latch **1314**. Note that the transistor **1308** may be part of or replaced with a switch or a switching circuit.

The DLL circuit **1302** increases circuit clock signal resolution and is in communication with the oscillator **1304** and the multiplexer **1312**. The DLL circuit **1302** is coupled to the multiplexer **1312** via delay line tap terminals **1316**. The latch **1314** is in communication with the DLL circuit **1302** and the multiplexer **1312**. The latch **1314** controls the variable state of the transistor **1308** based on signals received from the DLL circuit **1302** and the multiplexer **1312**. The latch **1314** may be a SR latch as shown or may be some other suitable latch or latching module.

The DLL circuit **1302** increases resolution and thus allows for fine tuning of a received clock signal **1320** from the oscillator **1304**. The DLL circuit **1302** provides small incremental delay line signals **1322** that are based on the clock signal **1320**. The incremental delay line signals **1322** may be referred to as taps  $TAP_{1-X}$ , where X is an integer that represents the total number of taps. The clock signal **1320** has an associated PWM period T for a given signal pulse. The multiplexer **1312** selects one of the taps  $TAP_S$  for the given modulated period T, where S is an integer value greater than zero (0) and less than or equal to X. Each tap has a corresponding initial pulse HIGH and/or ON state with a width  $\tau$ .

The tap selection is based on a PWM control signal **1324** generated by the PWM control module **1306**. The resolution of the free-running oscillation circuit **1300** is based on the pulse width  $\tau$  divided by the modulated period T ( $\tau/T$ ). When the tap  $TAP_X$  is selected, the free-running oscillation circuit **1300** is operating in a full ON state. In the full ON state the latch **1314** operates based on the PWM control signal **1324**.

Referring to FIG. **12**, a block diagram illustrating the free-running oscillation circuit **1300** undergoing calibration is shown. A calibration control module **1330** is coupled between the oscillator **1304** and the PWM control module **1306**. The oscillator **1304** is referred to as a primary oscillator for the described embodiment. Likewise, the clock signal **1320** is referred to as a primary clock signal **1320**. A lookup table **1332** is in communication with the calibration control module **1330**. In use, the primary oscillator **1304** generates the primary clock signal **1320**, which is received along with a reference clock signal **1334** by the calibration control module **1330**. The reference clock signal **1334** is generated by a reference oscillator **1336**. The calibration control module

1330 generates calibration control signals 1410, 1411 that are received by the PWM control module 1306 and may also be received by the lookup table 1332. Although the calibration control signals 1410, 1411 are shown as separate signals, they may be provided via the same signal line. As similarly described above, the lookup table 1332 may receive a condition signal 1340.

The DLL circuit 1302 includes a phase comparator 1350, a low pass filter 1352 and a delay line 1354, as well as a DLL circuit input 1356 and output 1358. The delay line 1354 delays the primary clock signal 1320 and has cascaded delay buffers 1360, which are coupled in series. The DLL circuit input 1356 is coupled to the primary oscillator 1304. The DLL circuit input 1356 is coupled to the phase comparator 1350 and the delay line 1354. The phase comparator 1350 compares phases of the primary clock signal 1320 and output of the delay line 1354. The phase comparator 1350 is coupled to the low pass filter 1352, which is in turn coupled to the delay line 1354. The DLL circuit output 1358 is coupled to the phase comparator 1350. Delay line tap terminals 1304 associated with each delay buffer 1360 are coupled to the multiplexer 1312.

Referring now also to FIG. 13, a flowchart illustrating a method of calibrating a free-running oscillation circuit is shown. The condition signal, 1340 corresponds to an environment, process, or other condition and is received in step 1400. In step 1402, the reference clock signal 1334 is received by the calibration control module 1330 from the reference oscillator 1336. In step 1404, the primary clock signal 1320 is also received by the calibration control module 1330 from the primary oscillator 1304.

A reference frequency of the reference clock signal 1334 is compared to a primary frequency of the primary clock signal 1320 in step 1406. In step 1408, the calibration control module 1330 determines whether the primary oscillator 1304 is operating at a correct frequency. Specifically, the calibration control module 1330 determines whether the primary frequency is within a margin of error of the reference frequency.

When the primary frequency is within the margin of error, the first calibration control signal 1410 is generated by the calibration control module 1330 based on the determination in step 1412. The first calibration control signal 1410 is stored with the measured condition value in the lookup table 1332. This process may be repeated for several condition values or states, and for one or more different conditions.

When data is taken at different temperatures, the first calibration control signal 1410 and the condition values and corresponding data can be read in step 1414. More data points can be interpolated, for example by use of curve fitting, in step 1416. The interpolated control signal values can be stored in step 1418. While this calibration technique is well suited to calibrate a free-running oscillator, it may be used for other circuits as well.

In step 1420, when the primary frequency is not within the margin of error, the calibration control module 1330 generates the second calibration control signal 1411 based on the determination. In step 1422, the PWM 1306 generates the PWM control signal 1324 based on the second control signal 1411. The PWM control signal 1324 has a variable duty cycle.

In step 1424, the delay line 1354 generates a delay line output signal 1425 based on the primary clock signal 1320. The primary clock signal 1320 is passed through the buffers 1360 to generate the delay line output signal 1425. In step 1426, the primary clock signal 1320 is compared with the generated delay line output signal 1425. The DLL circuit 1302 determines the phase difference between the primary clock signal 1320 and the delay line output signal 1425 and

generates a phase difference signal 1427. In step 1428, the phase difference signal 1427 is filtered to generate a filtered phase difference signal 1429, which is provided to a delay line 1354. In step 1430, the filtered phase difference signal 1429 is used as a loop control voltage, which is provided to the buffers 1360. Control may return to step 1424 upon completion of step 1430 and iteratively perform steps 1424-1430 to update the loop control voltage.

In step 1432, the PWM control signal 1324 is used to select a tap of the delay line 1354. For example only, the PWM control signal 1324 may be a digital control signal. The multiplexer 1312 selects a tap based on the PWM control signal to provide a selected delay line signal 1433 based on the selected taps in step 1434.

In step 1436, the latch 1314 generates an adjustment signal 1437 based on the delay line combined signal 1433 and the delay line output signal 1425. The capacitor 1310 is modulated to change the primary frequency based on the adjustment signal 1437, in step 1438. The above steps may be repeated with a new primary clock signal. The frequency of the new primary clock signal may be received and compared to a reference clock signal through repetition of the steps 1404-1408 and 1420-1438 and/or performance of the steps 1412-1418.

Referring to FIG. 14, a more detailed block diagram of a free-running oscillation circuit 1500 incorporating a DLL circuit 1502 is shown. The free-running oscillation circuit 1500 is similar to the free-running oscillation circuit of FIG. 5 in that it includes an oscillator 1502, a buffer 1504, a divide by N module 1506, a divide by M module 1508, a PWM control module 1510, a transistor 1512, a capacitor 1514, and a control signal generator 1516. The free-running oscillation circuit 1500 also includes the DLL circuit 1502, as well as a multiplexer 1518 and a latch 1520. The multiplexer 1518 and the latch 1520 are part of a DLL selection circuit 1521.

The DLL circuit 1502 includes a phase comparator 1522, a low pass filter 1524 and a delay line 1526 and has a DLL circuit input 1528 and output 1530. The phase comparator 1522 is coupled to the low pass filter 1524, which is in turn coupled to the delay line 1526, which has cascaded buffers 1527. The DLL circuit input 1528 is coupled to the divide by N and M modules 1506, 1508. The DLL circuit output 1530 is coupled to the latch 1520. The multiplexer 1518 selects one of tap outputs 1531 of the delay line 1526 based on a PWM control signal 1532 from the PWM control module 1510. The latch 1520 may be set and reset based on the selected tap outputs and a delay line output signal 1534 from the delay line output 1530.

The oscillator 1502 provides a primary clock signal 1540 to the buffer 1504. The buffer 1504 adjusts the amplitude and sharpens the edges of the primary clock signal 1540 provided by the oscillator 1502. The buffer 1504 may have a hysteresis characteristic to provide a substantially glitch free output signal.

A buffered oscillation signal 1542 out of the buffer 1504 is received by the divide by N module 1506. The divide by N module 1506 divides the frequency of the buffered oscillation signal 1542 by a factor of N to generate a divided clock signal 1544. The divided clock signal 1544 is reduced in frequency relative to the buffered oscillation signal 1542. The frequency of the divided clock signal 1544 may be further divided by the divide by M module 1508, which in turn generates an output signal  $V_{osc}$ . In other embodiments, other frequency dividers and multipliers may be used. These dividers may also be programmable.

The control signal generator 1516 receives a condition input signal 1546. The condition input signal 1546 may be

derived by the measurement of an environment, process, or other type of parameter. The control signal generator **1516** generates a condition control signal **1548** based on the condition input signal **1546**. The condition control signal **1548** may be stored in a lookup table **1547**.

The PWM control module **1510** provides the PWM control signal **1532** to the multiplexer **1518**. The PWM control signal **1532** may be generated based on the condition input signal **1546**. The PWM control module **1510** may access information stored in the lookup table **1547**. The PWM control module **1510** may generate the PWM control signal **1532** based on calibration information stored in the lookup table **1547**. The calibration information may be stored in the lookup table **1547** during a calibration period and later accessed during operation. For example, calibration information that is stored based on calibration control signals, such as the calibration control signals **1410**, **1411** of FIG. **12**, may be stored in the lookup table **1547** and used when generating the PWM control signal **1532**. The PWM control module **1510** may also or alternatively generate the PWM control signal **1532** based on condition information stored in the lookup table **1547** by the control signal generator **1516**.

The latch **1520** generates an adjustment signal **1550** that controls the impedance of transistor **1512**, which connects and disconnects capacitor **1514** from the oscillator **1502**. Changes in the duty cycle of the adjustment signal **1550** varies the effective capacitance of the capacitor **1514**, as seen by the oscillator **1502**. This in turn varies the oscillation frequency of the oscillator **1502**, and thus the frequency of the output signal  $V_{osc}$ . For this reason the transistor **1512** and the capacitor **1514** in combination form a variable capacitance circuit **1552** that receives the adjustment signal **1550** as an input signal.

Referring now also to FIG. **15**, a data flow diagram illustrating the operation of the free-running oscillation circuit **1500** is shown. The primary clock signal **1540** is generated in step **1600**. In step **1602**, amplitude of the primary clock signal **1540** is adjusted via the buffer **1504**. This has the effect of sharpening the edges and increasing the amplitude of the primary clock signal **1540** to generate the buffered oscillation signal **1542**. In step **1604**, the frequency of the buffered oscillation signal **1542** is divided to generate the divided clock signal **1544**, which is a frequency reduced relative to the buffered oscillation signal **1542**. In step **1606**, a measurement of a condition may be received and/or stored in the lookup table **1547**. For example, the condition input signal **1546** may be received by the control signal generator **1516**.

In step **1608**, the lookup table **1547** may be accessed to obtain calibration and/or condition information. In step **1610**, the PWM control signal **1532** may be generated based on information from the lookup table **1547** and based on the divided clock signal **1544**. In step **1612**, the delay line output signal **1534** is generated based on the divided clock signal **1544**.

In step **1614**, the divided clock signal **1544** is compared with the generated delay line output signal **1534**. The DLL circuit **1502** determines the phase difference between the divided clock signal **1544** and the delay line output signal **1534** and generates a phase difference signal **1615**. In step **1616**, the phase difference signal **1615** is filtered to generate a filtered phase difference signal **1617**, which is provided to the delay line **1526**.

In step **1618**, the filtered phase difference signal **1617** is used as a loop control voltage, which is provided to the buffers **1527** of the delay line **1526**. Control may return to step **1612** upon completion of step **1618** and iteratively perform steps **1612-1618** to update the loop control voltage.

In step **1620**, the PWM control signal **1532** is used to select tap outputs of the delay line **1526**, which is based on the frequency reduced clock signal **1544**. In step **1622**, a delay line combined signal **1623** is generated based on the selected tap outputs.

In step **1624**, an adjustment signal, such as the adjustment signal **1550**, is generated based on the delay line combined signal **1623** and the delay line output signal **1534**. The adjustment signal **1550** is used to set the frequency of the primary clock signal **1540** in step **1626**. Control may return to step **1600** upon completion of step **1626** and iteratively perform steps **1600-1626**. The steps **1600-1626** may be repeated with a new primary clock signal. The frequency of the new primary clock signal may be received and compared to a reference clock signal.

The above-described steps described with respect to the embodiments of FIGS. **4**, **6**, **13** and **15** are meant to be illustrative examples; the steps may be performed sequentially, synchronously, simultaneously, or in a different order depending upon the application.

Those skilled in the art can now appreciate from the foregoing description that the broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent to the skilled practitioner upon a study of the drawings, the specification, and the following claims.

What is claimed is:

**1.** An oscillation circuit comprising:

a delay lock loop circuit configured to generate (i) a plurality of incremental delay line signals and (ii) a delay line output signal, wherein the plurality of incremental delay line signals and the delay line output signal are generated based on a clock signal received from an oscillator;

a pulse-width modulation control module configured to generate a pulse-width modulation control signal;

a tunable circuit configured to adjust operation of the oscillator, the tunable circuit comprising

a transistor having a control terminal, a first terminal and a second terminal, the transistor configured to provide a variable impedance across the first terminal and the second terminal thereof based on an adjustment signal input to the control terminal, and

a capacitance in communication with the oscillator and one of the first and second terminals; and

a delay line selection circuit configured to generate the adjustment signal based on (i) the delay line output signal, (ii) the pulse-width modulation control signal, and (iii) one of the incremental delay line signals.

**2.** The oscillation circuit of claim **1**, wherein the delay line selection circuit comprises:

a multiplexer configured to select one of the plurality of incremental delay line signals based on the pulse-width modulation control signal; and

a latch configured to generate the adjustment signal based on (i) the selected one of the plurality of incremental delay line signals, and (ii) the delay line output signal.

**3.** The oscillation circuit of claim **1**, wherein the transistor adjusts current flowing to the capacitance based on the adjustment signal.

**4.** The oscillation circuit of claim **1**, wherein the delay line selection circuit is configured to adjust a charging time of the tunable circuit.



23

5. The oscillation circuit of claim 1, wherein the pulse-width modulation control module generates the pulse-width modulation control signal based on a condition signal.

6. The oscillation circuit of claim 5, wherein the condition signal is generated based on a measurement of at least one of an environment and a process.

7. The oscillation circuit of claim 1, wherein:

the delay lock loop circuit comprises a phase detector configured to detect a difference in phase between the received clock signal and the delay line output signal; and

the delay line output signal is generated based on the phase difference.

8. The oscillation circuit of claim 7, wherein:

the delay lock loop circuit further comprises a filter configured to generate a filtered difference signal based on the phase difference; and

the delay line output signal is generated based on the filtered difference signal.

9. The oscillation circuit of claim 1, further comprising a calibration control module configured to generate a calibration control signal based on the received clock signal,

wherein the pulse-width modulation control module generates the pulse-width modulation control signal based on the calibration control signal.

10. The oscillation circuit of claim 9, wherein the calibration control module generates the calibration control signal based on a reference clock signal.

11. The oscillation circuit of claim 9, wherein the calibration control module generates the calibration control signal based on a temperature signal.

12. The oscillation circuit of claim 1, further comprising: a calibration control module configured to generate a calibration control signal based on a temperature signal, wherein the pulse-width modulation control module generates the pulse-width modulation control signal based on the calibration control signal.

13. The oscillation circuit of claim 1, further comprising: a divide-by-N module configured to divide the received clock signal to generate a divided clock signal, where N is an integer greater than 1, wherein the delay lock loop circuit generates the plurality of incremental delay line signals and the delay line output signal based on the divided clock signal.

14. The oscillation circuit of claim 1, further comprising: a divide-by-N module configured to divide the received clock signal to generate a divided clock signal, where N is an integer greater than 1, wherein the pulse-width modulation control module generates the pulse-width modulation control signal based on the divided clock signal.

15. The oscillation circuit of claim 14, wherein: the pulse-width modulation control module generates the pulse-width modulation control signal based on (i) the divided clock signal, and (ii) a received condition signal, and

wherein the condition signal is generated based on a measurement of at least one of an environment and a process.

16. The oscillation circuit of claim 1, wherein: the pulse-width modulation control module generates the pulse-width modulation control signal based on entries in a lookup table, and the pulse-width modulation control module generates the pulse-width modulation control signal based on temperature entries in the lookup table.

24

17. An oscillation circuit comprising:

a delay lock loop circuit configured to generate (i) a plurality of incremental delay line signals and (ii) a delay line output signal, wherein the plurality of incremental delay line signals and the delay line output signal are generated based on a clock signal received from an oscillator;

a pulse-width modulation control module configured to generate a pulse-width modulation control signal;

a tunable circuit configured to adjust operation of the oscillator, the tunable circuit comprising a capacitance in communication with the oscillator, and a first circuit in communication with the oscillator and configured to adjust current supplied to the capacitance based on an adjustment signal; and

a delay line selection circuit configured to generate the adjustment signal based on (i) the delay line output signal, (ii) the pulse-width modulation control signal, and (iii) one of the incremental delay line signals.

18. The oscillation circuit of claim 17, wherein the delay line selection circuit comprises:

a multiplexer configured to select one of the plurality of incremental delay line signals based on the pulse-width modulation control signal; and

a latch configured to generate the adjustment signal based on (i) the selected one of the plurality of incremental delay line signals, and (ii) the delay line output signal.

19. A circuit comprising:

a delay lock loop circuit configured to generate (i) a plurality of incremental delay line signals and (ii) a delay line output signal, wherein the plurality of incremental delay line signals and the delay line output signal are generated based on a clock signal received from an oscillator;

a pulse-width modulation control module configured to generate a pulse-width modulation control signal;

a tunable circuit configured to adjust operation of the oscillator, the tunable circuit comprising a capacitance in communication with the oscillator, and a variable impedance circuit in communication with the oscillator, wherein the variable impedance circuit is configured to vary an impedance of the variable impedance circuit based on an adjustment signal; and

a delay line selection circuit configured to generate the adjustment signal based on (i) the delay line output signal, (ii) the pulse-width modulation control signal, and (iii) one of the plurality of incremental delay line signals, wherein the delay line selection circuit includes a device, and wherein the device is configured to receive (i) the delay line output signal, and (ii) a selected one of the plurality of incremental delay line signals.

20. A circuit comprising:

a delay lock loop circuit configured to generate (i) a plurality of incremental delay line signals and (ii) a delay line output signal, wherein the plurality of incremental delay line signals and the delay line output signal are generated based on a clock signal received from an oscillator;

a pulse-width modulation control module configured to generate a pulse-width modulation control signal;

a tunable circuit configured to adjust operation of the oscillator, the tunable circuit comprising a capacitance in communication with the oscillator, and a variable impedance circuit in communication with the oscillator, wherein the variable impedance circuit is configured to vary an impedance of the variable impedance circuit based on an adjustment signal; and

## 25

a delay line selection circuit configured to generate the adjustment signal based on (i) the delay line output signal, (ii) the pulse-width modulation control signal, and (iii) one of the plurality of incremental delay line signals, wherein the delay line selection circuit comprises

a multiplexer configured to select one of the plurality of incremental delay line signals based on the pulse-width modulation control signal; and

a latch configured to generate the adjustment signal based on (i) the selected one of the plurality of incremental delay line signals, and (ii) the delay line output signal.

21. A circuit comprising:

a delay lock loop circuit configured to generate (i) a plurality of incremental delay line signals and (ii) a delay line output signal, wherein the plurality of incremental delay line signals and the delay line output signal are generated based on a clock signal received from an oscillator;

## 26

a pulse-width modulation control module configured to generate a pulse-width modulation control signal;

a tunable circuit configured to adjust operation of the oscillator, the tunable circuit comprising

a capacitance in communication with the oscillator, and

a variable impedance circuit in communication with the oscillator, wherein the variable impedance circuit is configured to vary an impedance of the variable impedance circuit based on an adjustment signal, wherein the variable impedance circuit comprises a transistor, wherein the transistor comprises a control terminal, and wherein the control terminal is configured to receive the adjustment signal; and

a delay line selection circuit configured to generate the adjustment signal based on (i) the delay line output signal, (ii) the pulse-width modulation control signal, and (iii) one of the plurality of incremental delay line signals.

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